INSTITUT FÜR BAUSTOFFE, MASSIVBAU UND BRANDSCHUTZ

AMTLICHE MATERIALPRÜFANSTALT FÜR DAS BAUWESEN

TU BRAUNSCHWEIG

Testing of High-Strength LWA-Concrete at High Temperatures

Test Report

prepared by

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Project Client: CONOCO NORWAY INC.

Service Order No. TLP-278, dated October 2, 1991

Content

1. Introduction

Conoco Norway Inc. commissioned the Institut für Baustoffe, Massivbau und Brandschutz under service order No TLP-278 dated 10-02-1991 to perform tests on the high temperature behaviour of high-strength light weight aggregate concrete (HS-LWA-Concrete).

The aim of the study outlined in the following was to gather reliable strength data of high-strength LWA concrete at temperatures which may occur during a fire accident.

The experiments became necessary because, up to now, high temperature data are only available for ordinary-strength LWA concrete [1, 2]. On the other hand, experiments with high-strength normal density concrete have shown that such (ordinary strength concrete) data cannot be simply extended (e. g., by linear extrapolation) to high-strength concrete. Due to its special composition and microstructure high-strength concrete exhibits high temperature phenomena not seen with ordinary strength concrete [3].

It was intended to study the high temperature strength of HS-LWA-concrete by testing cylindrical specimens (ø 80 mm, length ≈ 300 mm) at 5 different temperatures, using 2 to 3 specimens at each test temperature. According to RILEM-recommendations [4], cylindrical specimens (minimum ø 80 mm) should be heated without load to the desired maximum temperature (heating rate ca. 2 K/min), maintained at constant temperatures for 2 hours to ensure uniform temperature distribution through the specimens cross sections, and then tested at high temperatures by strain-controlled σ-ϵ-tests. Also some pilot tests concerning residual strength and deformation properties were planned to be conducted.

The tests had to be carried out according to the test program suggested by the Institut für Baustoffe, Massivbau und Brandschutz and amended by Conoco Norway Inc. (see Proposal "Tests Concerning Strengths of High-Strenth LWA-Concrete at High Temperatures", 188/Di/Me dated from 08-22-1991, version revised by Conoco Norway Inc. dated 10-02-1991).

2. Experimental programm

2.1 Reference tests

Besides reference tests performed elsewhere with cubes (100 x 100 x 100 mm^3) of the same batches as the cylinders at IBMB, 2 to 3 cylindrical specimens (ø

80 mm, l = 300 mm) were tested to obtain 20 °C-reference data, too (see test matrix given in table 1). After determination of the modulus of elasticity, the σ-ϵ-lines and the strength, resp., the residual of the cylindrical specimens were dried at 105 °C to determine the amount of evaporable water in each specimen, which may be of interest with respect to spalling phenomena, specific loss of strength at 100...200 °C etc.

Table 1: Number of specimens investigated at ambient temperature (reference tests).

Specimens #, Contractor 1	Specimens #, Contractor 2
3 (+ 2)	2 (+ 2)

The number of tests shown in brackets have been carried out in addition to ordered tests.

2.2 σ-ϵ-tests at high temperatures

The proposed steady state σ-ϵ-tests are shown in table 2. The number of tests shown in brackets have been conducted in addition to the ordered tests.

Table 2: Number of specimens investigated at elevated temperatures (σ-ϵ-tests)

temperature level	Specimens #, Contractor 1	Specimens #, Contractor 2
100 °C	3	-
250 °C	2 (+ 1)	2
450 °C	2	2
600 °C	2	3

The testing procedure was as follows:

- Installation of specimens, 3 times loading and unloading of the specimens (to measure the modulus of elasticity) at ambient temperature.

- Heating of the specimens without load to the desired test temperature (heating rate 2 K/min).

- After reaching the test temperature, the specimens were maintained at constant temperature for 2 hours, to eliminate internal thermal gradients.

- Strain-rate-controlled σ-ϵ-tests were then performed at the specified temperature.

The deformation and load of the specimens had to be measured during all phases of the test (incl. heating phase).

2.3 Residual σ-ϵ-tests

Residual σ-ϵ-tests were also conducted on specimens to obtain information concerning the behaviour of the material after fire exposure, which is of interest with respect to assessments of residual bearing capacity, repairability studies etc.

In general, for these tests one specimen of contractor 1 and contractor 2 were tested at each test temperature as shown in table 3. Additionally, 2 specimens of contractor 2 heated to 250 °C were tested to obtain information concerning scattering of the strength and elastic modulus data. At the end, one extra test (put in brackets in table 3) was conducted.

Table 3: Number of specimens tested after heating to the given temperatures and cooling to ambient temperature (residual σ-ϵ-tests)

temperature level	Specimens #, Contractor 1	Specimens #, Contractor 2
100 °C	1	1
150 °C	1	1
200 °C	1	1
250 °C	1	3 (+ 1)
350 °C	1	1

The testing procedure include the following steps:

- After installation, specimens were loaded and unloaded 3 times to measure the modulus of elasticity at ambient temperature.

- Specimens where then heated without load to the desired test temperature (heating rate 2 K/min).

- After reaching the specified temperature, specimens were maintained at constant temperature for 2 hours to eliminate internal thermal gradients. Subsequently they were cooled to ambient temperature (cooling rate $\leq$ 2 K/min).

- Strain-rate-controlled σ-ϵ-tests were then performed at ambient temperature.

The deformation and load of the specimens had to be measured during all phases of the test (incl. heating and cooling).

3. Testing and results

On October 1, 1991, the Institut für Baustoffe, Massivbau und Brandschutz received 20 cylindrical specimens from the contractor 1. The specimens were drilled out of a big concrete slab, and had a diameter of about 84 mm and a length of about 400 mm. The specimens were continuously marked HP 1 to HP 20 and cut to a length of 300 mm by a water cooled diamond saw. Afterwards the two loading surfaces of the specimens were ground plane and parallel to each other.

The high temperature testing machine was equipped with loading plates for testing specimens with a diameter of 80 mm. Because of the bigger diameter of the specimens and for a easier installation of specimens, at first one of the loading surfaces of the specimens were bevelled with an angle below 45°. After running several tests, a decrease of the compressive strength due to this bevelling was observed. Therfore, for the further tests bigger loading plates and specimens without bevelled head faces were used to avoid the need to bevel the head faces of the specimens.

On October 10, 1991, 21 cylindrical specimens were received from the contractor 2 and marked HP 2-1 up to HP 2-21. These specimens had a diameter of about 79.4 mm and length of about 400 mm. They were prepared in the same way as the specimens from contractor 1.

3.1 Testing

The tests were carried out according to the testing procedure described in Chapter 2.

3.2 Reference tests

Before performing the compressive tests the weight and dimensions of each specimen were measured to determine the bulk density. These measurements are compiled in tables 4 and 5 for the specimens of contractor 1 and 2, resp. (for further details see testing records given in the appendix A1 and A2).

After determing the bulk density, the specimens were tested to determine their modulus of elasticity and compressive strength. Tables 4 and 5 show the obtained results. With specimen nr. HP 2-1 and HP 2-2 the Young's modulus was measured according to the German Standard DIN 1048. The respective testing records can be found in the appendix parts A3 up to A6. Young's modulus has been here defined as the secant modulus of the tenth loading.

For estimating the effect of the varying stiffness of the different testing machines used in these tests on the measured compressive strength data, tests with the 400 kN high temperature testing machine (see fig. 1) were performed at 20 °C in addition to the described tests with a 2000 kN testing machine in hall 1 of the institute (see fig. 2). The respective results of these tests are also shown in table 4 and 5 (for details see appendix A7 and A8).

The results show that there is no significant influence of the testing devices on the measured Young's modulus. However, the strength data do show some variation with respect to the testing machine used. The strength values obtained with the 400 kN testing machine are about 8 % lower for the specimens in series HP and about 2.5 % lower for the specimens series HP 2 than the strength values obtained with the 2000 kN testing machine, which has a considerable higher stiffness than the 400 kN high temperature testing machine.

Summarizing the results, it can be stated that the specimens of contractor 1 and contractor 2 have nearly the same bulk density and show the same behaviour regarding elasticity and compressive strength. With respect to strength it should be kept in mind that the specimens of the contractor 1 (diameter of about 84 mm) are less slender than the specimens of the contractor 2 (diameter of about 80 mm).

3.3 Moisture content of the specimens

The moisture content of the specimens was determined by drying (at 105 °C) pieces of the specimens HP1, HP2, HP2-1 and HP2-2 which were crushed during the compression strength tests. Moisture content data are given in appendix A1 and A2. The mean moisture content of the specimens of contractor 1 was 8.76 % related to the dry weight of the specimens; specimens of contractor 2 contained 8.88 % moisture.

Table 4: Test results of the 20 °C-reference tests with cylindrical specimens (ø 84 mm, l = 300 mm) of Contractor 1.

specimen nr.	density, kg/dm³	moisture cont., %	compressive strength, N/mm²	E-modulus, kN/mm²	remarks
HP-1	1,937	8,80	62,4	-	tested at Hall I,
HP-2	1,932	8,72	65,8	-	2000-kN testing
x	1,935	8,76	64,1	-	machine
HP-3*)		-	44,1 *)	23,8*)	tested at the high
HP-4	-	-	57,9	23,9	temp. testing machine
HP-20*)	-	-	59,6*)	-	tested at Hall I, 2000 kN-testing machine

*) Specimens with bevelled head faces.

Table 5: Results of the 20 °C-reference tests with cylindrical specimens (ø 80 mm, l = 300 mm) of Contractor 2

specimen nr.	density, kg/dm³	moisture cont., %	compressive strength, N/mm²	E-modulus, kN/mm²	remarks
HP2-1 in	1,915	8,62	61,0	23,3	tested at Hall I,
HP2-2	1,938	9,13	63,4	24,0	2000 kN-testing
x	1,927	8,88	62,2	23,6	machine
HP2-8	-		63,1	25,5	tested at the high
HP2-9	-		58,3	23,1	temperature testing
x					machine

3.4 High temperature behaviour

3.4.1 Strength and elasticity at high temperatures

The results from individual σ-ϵ-tests are shown in appendix A9 to A18. A compilation of the σ-ϵ-curves obtained at various test temperatures is given in figures 3 and 4. The diagrams indicate that the strain-controlled tests were terminated after achieving the maximum load to avoid the damage of the dilatometer systems from explosive failure of the specimens. The achieved maximum stress values have been used to define the strength of the tested specimens.

The σ-ϵ-diagrams show at temperatures up to 250°C nearly no significant inclination of the σ–ϵ-curves until the unset of failure of the specimens. Failure of the specimens occured almost without warning, like an explosion, accompanied with a loud bang. At higher temperatures, from about 450°C onwards, the σ–ϵ-curves indicate some inelastic deformation prior to failure.

With regard to the failure behaviour, two modes of failure have been observed (see fig. 5...12): up to 250°C surfaces of fracture were rather smooth and also went always through the aggregates. At 450°C and 600°C the surfaces of fracture where mainly located in the matrix and in the interfacial zone between matrix and coarse aggregates. They surrounded more or less the aggregates. This behaviour indicates a significant loss of the matrix strength and the bond between matrix and lightweight aggregates when temperature is exceeding 250 °C.

Up to 150 °C the organic fibres remained unchanged in the concrete with respect to their shape, dimension and mechanical strength. With specimens which were heated up to 200°C or more the fibres were molten.

The obtained strengths and the Young's modulus values are compiled in table 6 and 7. In figure 13 and 14 the respective diagrams are indicated. It can be seen that the strength of the specimen decreases by about 20 % at 100°C compared to the initial strength. At about 250°C there appears to be a slight recovering of the strength. Above 250 °C, with the further increase of temperature, the strength monotonically decreases.

Table 6: Results of the high temperature investigations with cylindrical specimens (ø 84 mm, l = 300 mm) of Contractor 1

specimen nr.	test temperature	compressive strength, N/mm^2	E-modulus, kN/mm^2	remarks
HP-7	100 °C	47,3	20,9	tested at the high temp. testing machine,
HP-13	100 °C	49,8	20,2	400 kN- testing machine
HP-14	100 °C	47,8	20,5	
HP-5+)	250 °C	45,9	18,0	
HP-8	250 °C	56,8	17,2	
HP-12	250 °C	57,9	16,9	
HP-6+)	450 °C	36,2	14,2	
HP-9	450 °C	37,2	12,5	
HP-10	600 °C	24,5	9,4	
HP-11	600 °C	24,6	9,2	
HP-15	100 °C, res. *)	62,7	20,9	tested at Hall I, 2000 kN-testing machine
HP-16	150 °C, res.	61,1	18,0	
HP-17	200 °C, res.	61,5	14,9	"
HP-19	250 °C, res.	55,8	14,2	tested at the high temperature testing machine, 400 kN-testing machine
HP-18	350 °C, res.	44,4	14,0	

+) Specimens with bevelled head faces

*) Residual tests

Table 7: Results of the high temperature investigations with cylindrical specimens (ø 80 mm, l = 300 mm) of contractor 2

specimen nr.	test temperature	compressive strength, N/mm^2	E-modulus kN/mm^2	remarks
HP2-10	250 °C	58,6	17,2	tested at the high temperature testing machine 400 kN-testing machine
HP2-11	250 °C	54,2	16,6	
HP2-12	450 °C	33,0	12,5	
HP2-13	450 °C	31,6	12,1	
HP2-14	600 °C	20,3	8,3	
HP2-15	600 °C	20,8	9,2	
HP2-16	600 °C	20,1	7,9	
HP2-3	100 °C, res.	61,1	20,6	tested at Hall I, 2000 kN-testing machine
HP2-4	150 °C, res.	60,8	19,0	
HP2-5	200 °C, res.	57,9	18,0	"
HP2-6	250 °C, res.	49,2	14,1	tested at the high temperature testing machine
HP2-17	250 °C, res.	51,4	14,2	"
HP2-7	350 °C, res.	42,0	12,2	"
HP2-18	250 °C res.	44,9	12,0	tested at Hall I, 2000 kN-testing machine
HP2-19	250 °C res.	43,5	12,3	

Furthermore the tables and figures show that Young's modulus also decreases about 20 % at 100°C. Unlike the strength however, Young's modulus decreases monotonically with increase of the tests temperature, i. e., no recovery at 250 °C.

3.4.2 Residual strength and elasticity properties

The results of the individual tests are compiled in the appendix parts A19 to A39. Compilations of these results are given in table 6 and 7 and figures 15 to 18, resp.

Two different procedures were used for testing the residual strength of the specimens. In the first method, specimens were installed into the high temperature testing machine and heated with the constant heating rate of 2 K/min to the desired maximum temperature. After reaching it the temperature level was held constant for two hours to achieve thermal equilibrium within the specimens. Then the specimens were cooled to room temperature (cooling rate < 2 K/min) and tested. Before running the σ–ϵ-tests, the specimens were loaded and unloaded three times to determine Young's modulus.

In the second method the specimens were treated with the same temperature regime used in the method described above. The testing, however, was carried out with the 2000 kN-testing machine in hall 1 of the institute. For determining the Young's modulus the specimens were loaded and unloaded ten times, where the maximum stress load was chosen one third of the expected ultimate stress (see appendix A21 and A25).

The obtained σ-ϵ-curves show, that after the first loading-unloading-cycle a residual shortening which strongly increases with the increase of the maximum temperature. - The specimen HP17, for example, indicated a residual shortening of about 0.2 ‰ after heating to 200°C.

With application of further loading cycles, a nonlinearity in the σ–ϵ-curve occured which also increased with increasing maximum temperatures. Due to this nonlinearity the Young's modulus at higher temperatures strongly depends on its definition. For example, if it is calculated as the tangent modulus, the Young's modulus cover a range of ± 100 % depending where the tangent is taken from σ–ϵ-curve, at small stresses or at high stresses. Here, the Young's modulus was determined as the secant modulus at the tenth loading-unloading-cycle.

The specimens tested in the cold state also showed scarcely any plastic deformations up to failure as long as the maximum temperature was lower than 250 °C (see appendix parts A22, A24 and A26). Also, up to 250 °C the specimens failed suddenly without any warning. - In one of the tests the dilatometer of the high temperature testing device was damaged during such an explosive failure by concrete pieces. Thus, it had to be replaced by a new one.

At maximum temperatures above 350°C the failure of the specimens was indicated by a decreasing slope of the σ–ϵ-curve (see appendix part A34), and the specimens failed in a rather ductile way.

The measured compressive strength and Young's modulus values compiled in tables 6 and 7, respectively plotted in figs. 17 and 18. The data indicate contrarily to the strengths determined at elevated temperatures, that the residual strength decreases very little in the temperature range 100°C to 200°C. At higher temperatures (250 °C to 350 °C) there is hardly a difference between the strength values determined at elevated temperatures and the residual strength values.

Furthermore, the results indicate that there is only a very small difference between the Young's modulus of the specimens tested at high temperatures and that of specimens tested after cooling.

3.4.3 Thermal expansion

The thermal expansion was determined only with specimens heated up to 600 °C, because, for lower temperatures the risk of damaging the glass rods of the dilatometer system (necessary for determining the thermal expansion) during explosive failure of the specimens was too high.

The results from these tests are compiled in the appendix A40 up to A42. A comparison of the thermal expansion of the various specimens is made in Figs. 19 and 20. As can be seen, in the temperature range up to 570 °C the specimens indicate a nearly linear expansion. At about 570°C there is a slight step of the thermal expansion which is caused by the quartz inversion (α- → β-quartz) of the quartzitic sand which the fine mortar contains.

Often, at about 600 °C a further increase of the thermal expansion can be observed. This increase is caused by the thermal homogenization of the specimens. During heating the temperature of the specimen center is somewhat below its surface temperature. During the hold time period the center temperature rises until it reaches the surface temperature, which is kept constant. Thus, the mean specimen temperature still rises and causes a further expansion although the measured temperature has reached its constant level.

4. Summary

Two series of 20 cylindrical specimens, each made with high-strength light-weight-aggregate concrete (HS-LWA concrete) by two different contractors, were tested to determine the compressive strengths and the Young's modulus at high temperatures as well as after cooling to ambient temperature.

The test results show that there is hardly any difference in the mechanical behaviour between the specimens made by the different contractors. This holds for the reference strength, the high temperature strength, and the residual strength data as well.

Specimens tested at a temperature of 100°C indicate a loss of strength of about 20 % compared to unheated concrete. At 250 °C a strength recovery occurs and the loss of strength is significantly smaller than at 100 °C. At higher temperatures the strength decreases monotonically to about 38 % of the 20 °C-reference strength.

The residual strength of specimens heated up to 100°C and tested after cooling at room temperature shows a significantly lower loss of strength then the specimens tested at 100 °C. From 200°C onwards the strength decrease of the specimens tested at room temperature after heat exposure is similar to that of specimens tested at elevated temperatures, and only small differences between the residual strength and high temperature strength occured.

The modulus of elasticity indicated a monotonic decrease with increasing temperature. There were hardly any differences between specimens which were tested at high temperatures and specimens which were tested in the cold state after heating.

The thermal expansion was determined up to 600°C. There were no differences among the tested specimens. In the temperature range up to 500°C the mean value of the coefficient of thermal expansion amounted 0.8 x 10^{-5} 1/K. Above 570 °C, exceeding the quartz transition temperature, the thermal expansion reaches a maximum value of 6 ‰.

7. References

[1] Schneider, U.; Diederichs, U.; Rosenberger, W. and Weiß, R.: Hochtemperaturverhalten von Festbeton (High temperature behaviour of concrete), Sonderforschungsbereich 148, Arbeitsbericht 1978 - 1980, Teil II, B3-1 - 142, Technical University Braunschweig, 1980.

[2] Schneider, U. (Editor): Properties of Materials at High Temperatures - Concrete. Report RILEM COMITTEE 44-PHT. Department of Civil Engineering, Gesamthochschule Kassel, 1985.

[3] Diedericht, U.; Jumppanen, U-M. & Penttala, V.:
Behaviour of high strength concrete at high temperatures, Helsinki University of Technology, Department of Structural Engineering, Report 92. Espoo 1989, 76 p.

[4] Schneider, U. (Editor):
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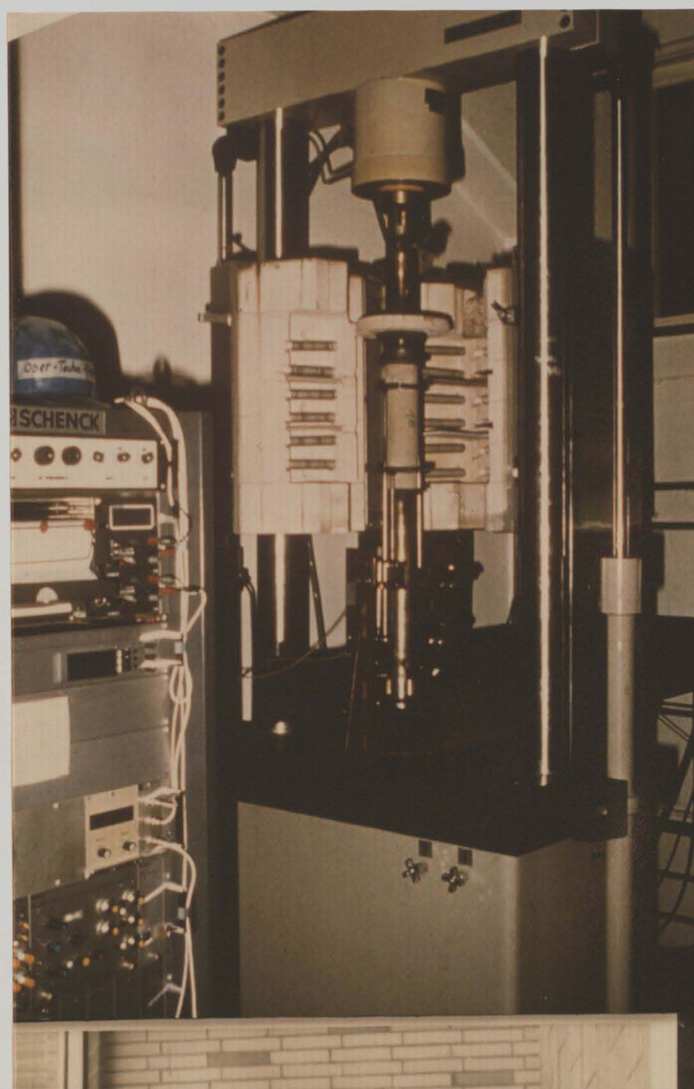


Fig. 1: 400 kN-high temperature testing machine with installed specimen.

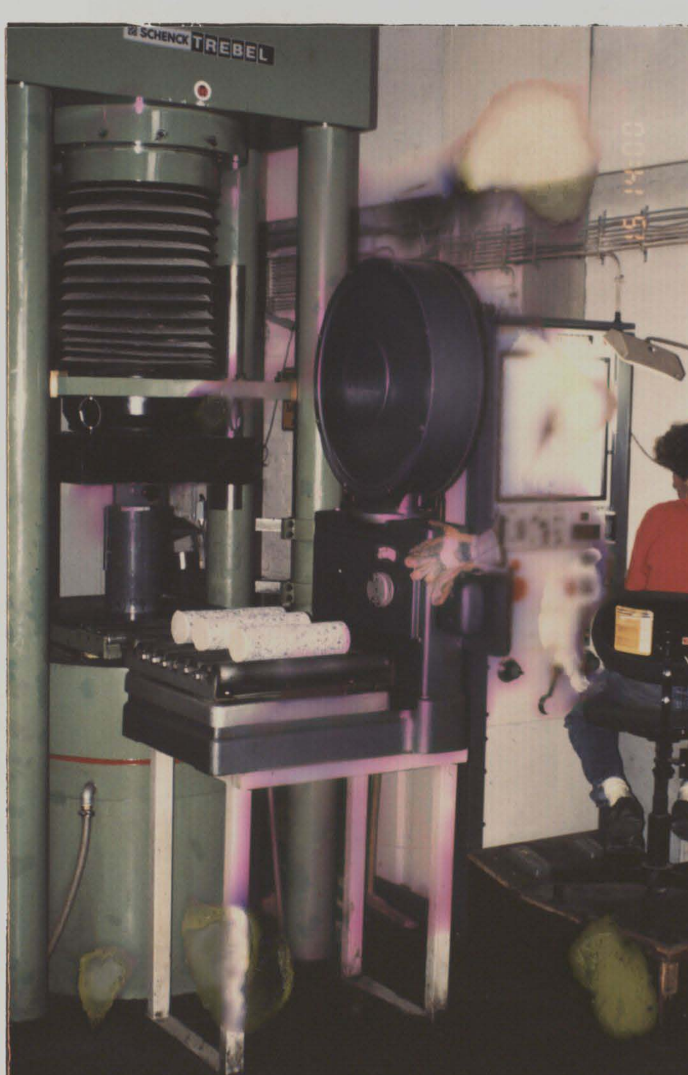


Fig. 2: Installation of a prepared HS-LWA specimen into the 2000-kN-testing machine.

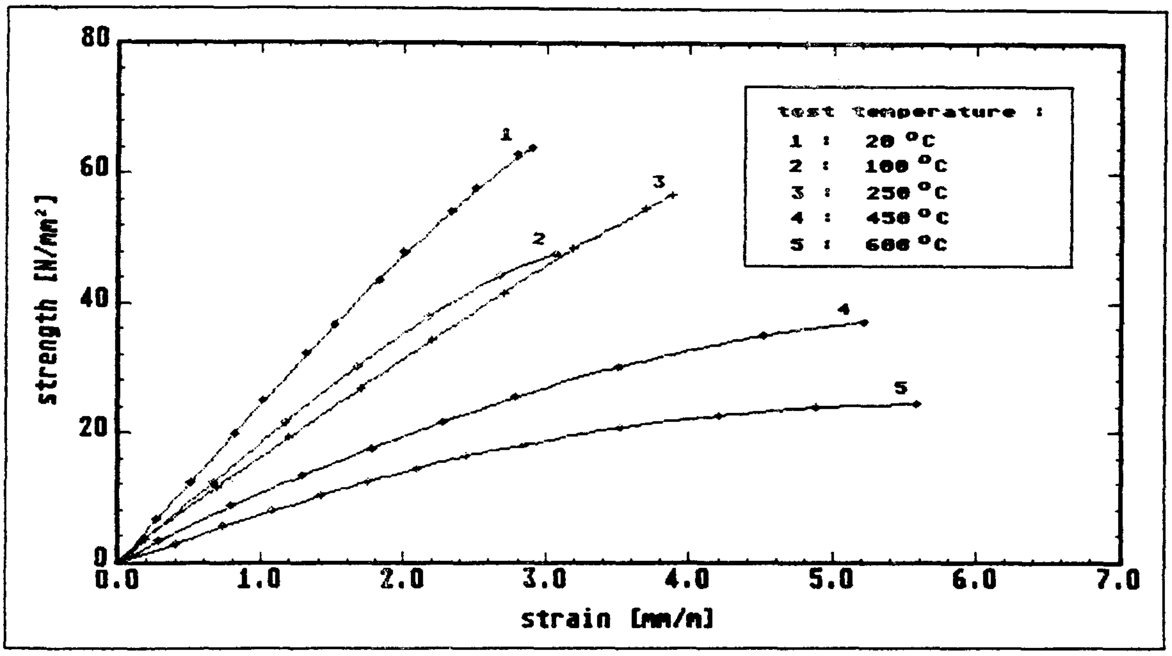


Fig. 3: σ-ϵ-relationships measured at high temperatures with HS-LWA-concrete specimens of contractor 1.

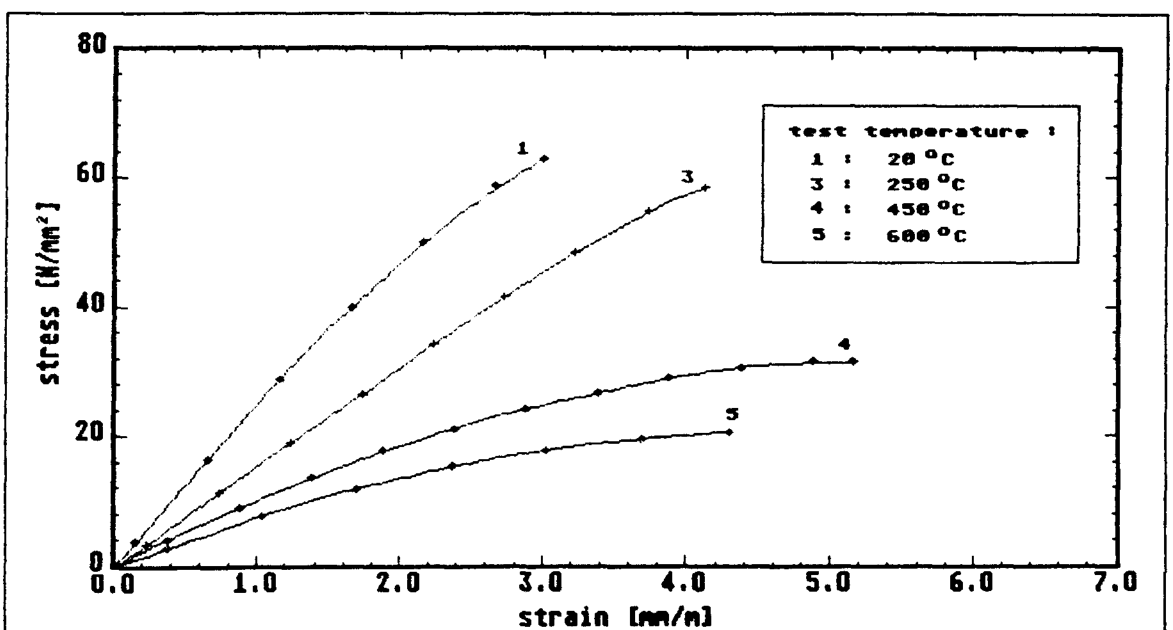


Fig. 4: σ-ϵ-relationships measured at high temperatures with HS-LWA-concrete specimens of contractor 2.

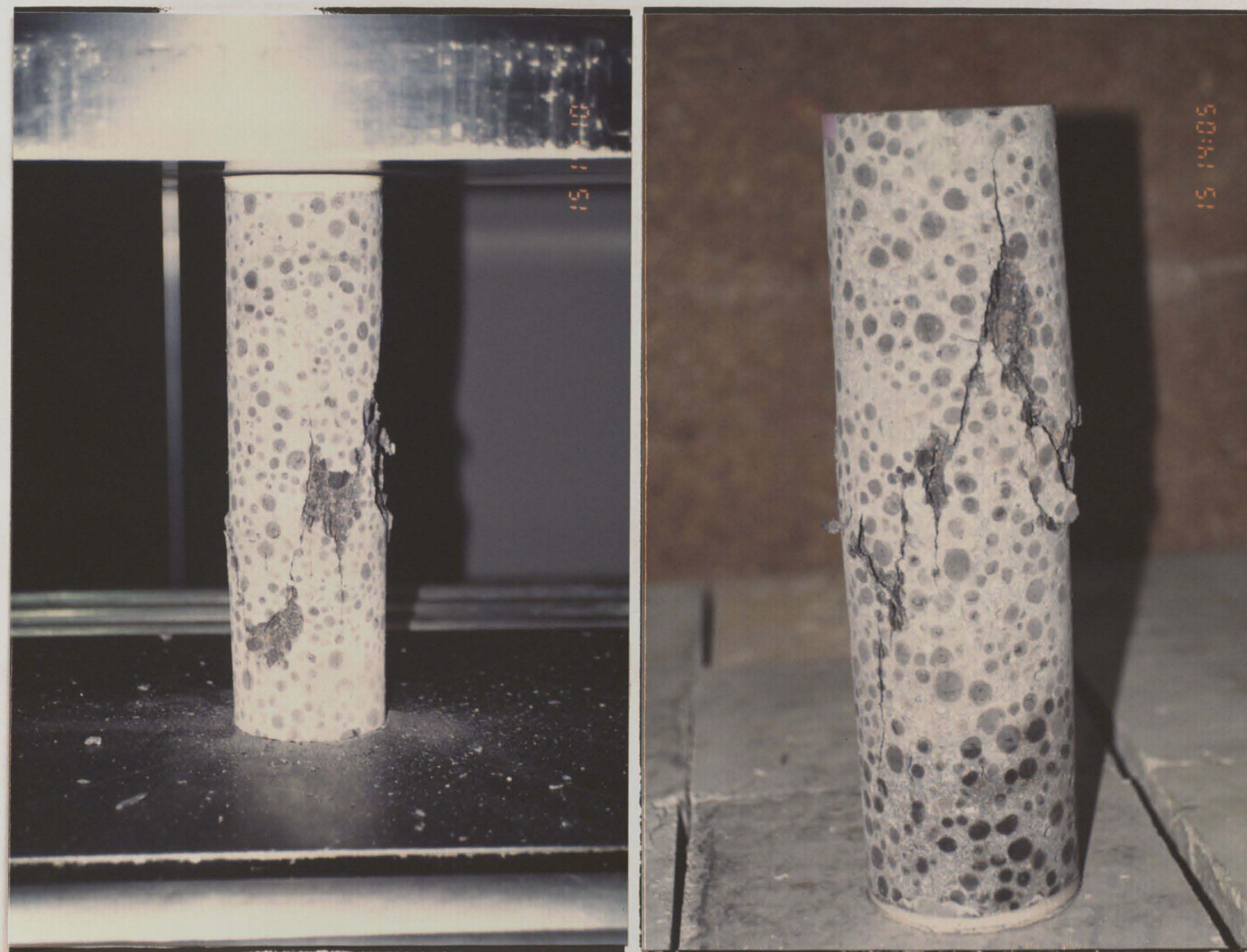


Fig. 5: Specimens after termination of the reference strength test.

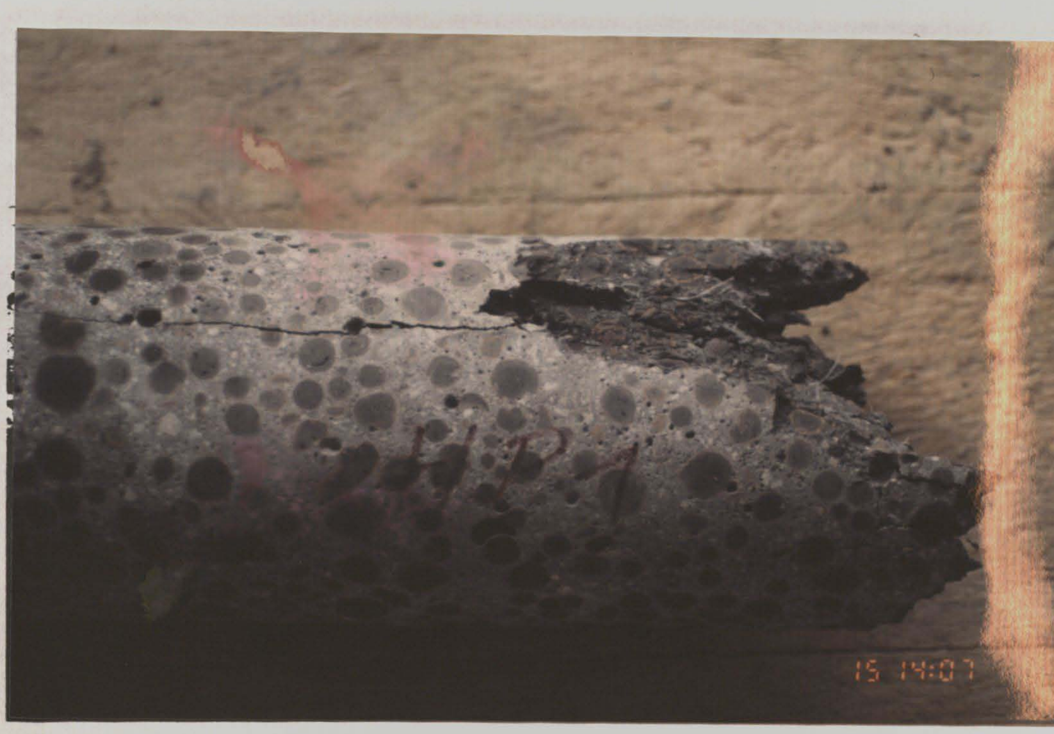


Fig. 5: Tested specimen HP-1. Adjacent to the fracture surface the organic fibres are visible.

Fig. 7: Fracture surface of specimen HP-1. It can be seen, that the surface of fracture is rather plane and also crosses the aggregates.

Fig. 8: Specimen after termination of the residual strength test (max. temp. 100 °C). The organic fibres are visible on the fracture surfaces.

Fig. 9: Specimen after termination of the residual strength test (max. temp. 150 °C). On the fracture surfaces the organic fibres are still visible.

Fig. 10: Specimen after termination of the residual test (max. temp. 250 °C). The fracture surfaces surround more often the light weight aggregates. No fibres are visible anymore.

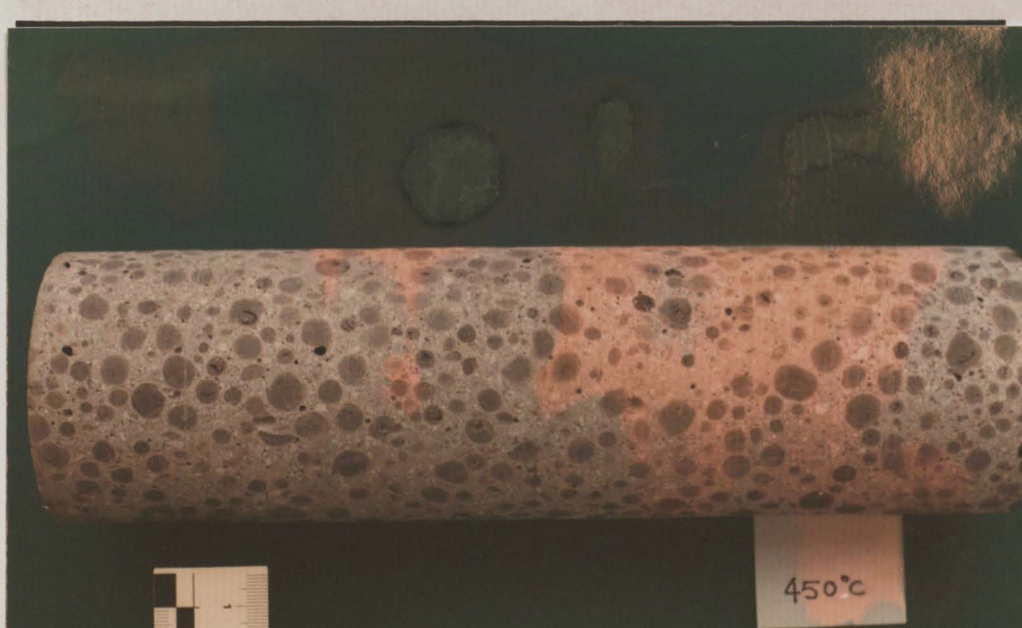


Fig. 11: Specimen tested at 450 °C. The colour of the matrix and the aggregate turned a little bit brown due to oxidation of their iron compounds (comp. Figs. 8 to 10).

Fig. 12: Specimens tested at 600 °C. The colour of the matrix and the aggregate turned orange due the increased oxidation of the iron compounds (comp. Figs. 8 to 11).

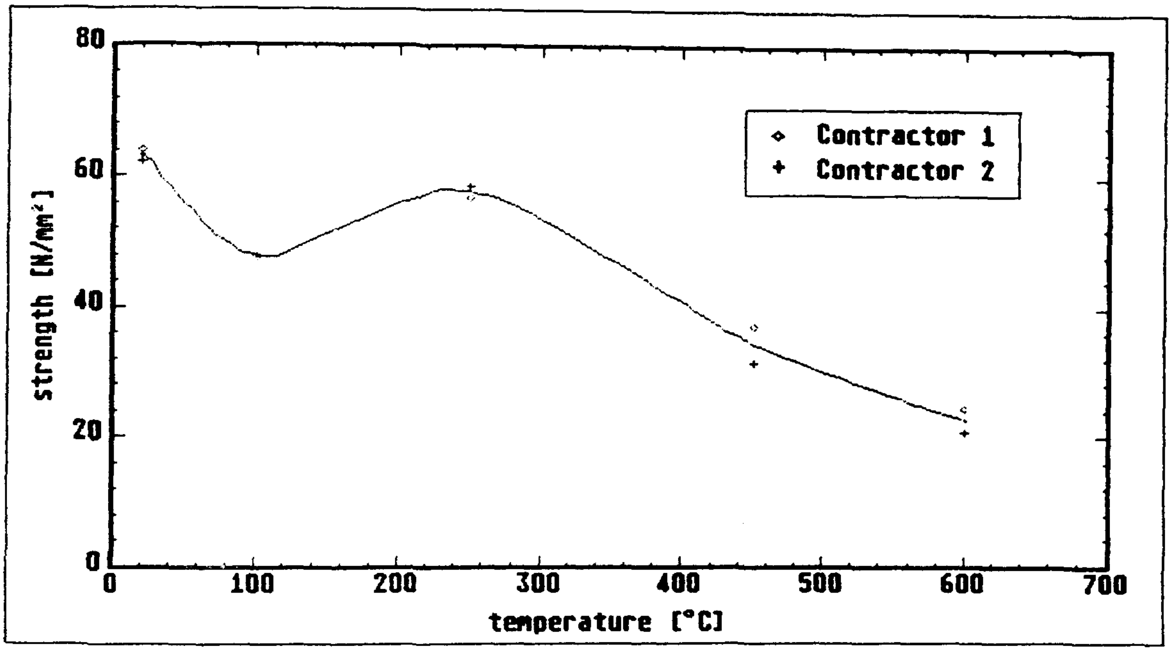


Fig. 13: Compressive strength of HS-LWA-concrete at high temperatures.

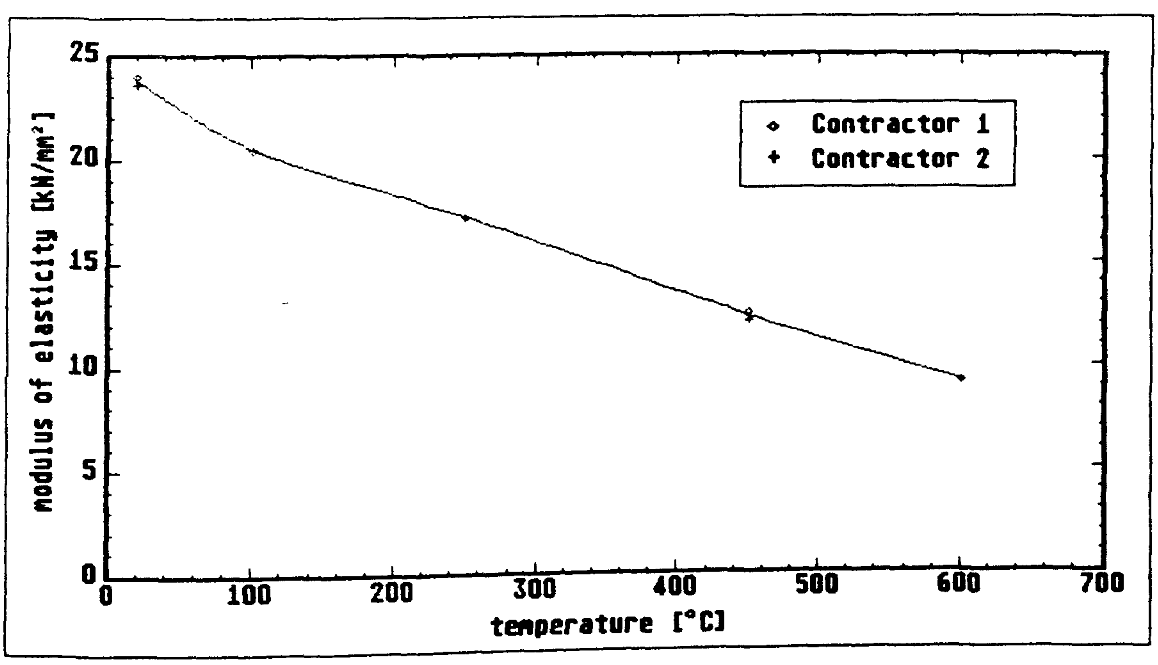


Fig. 14: Modulus of elasticity of HS-LWA-concrete at high temperatures.

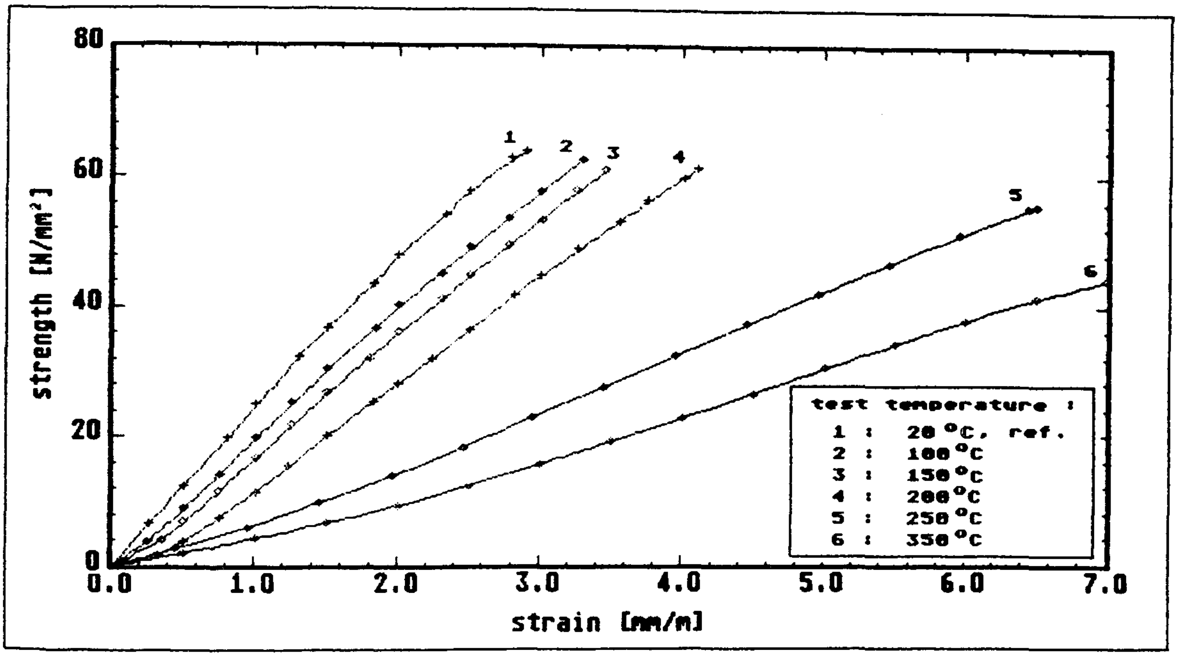


Fig. 15: Residual σ-ϵ-relationships measured with HS-LWA-concrete specimens of contractor 1.

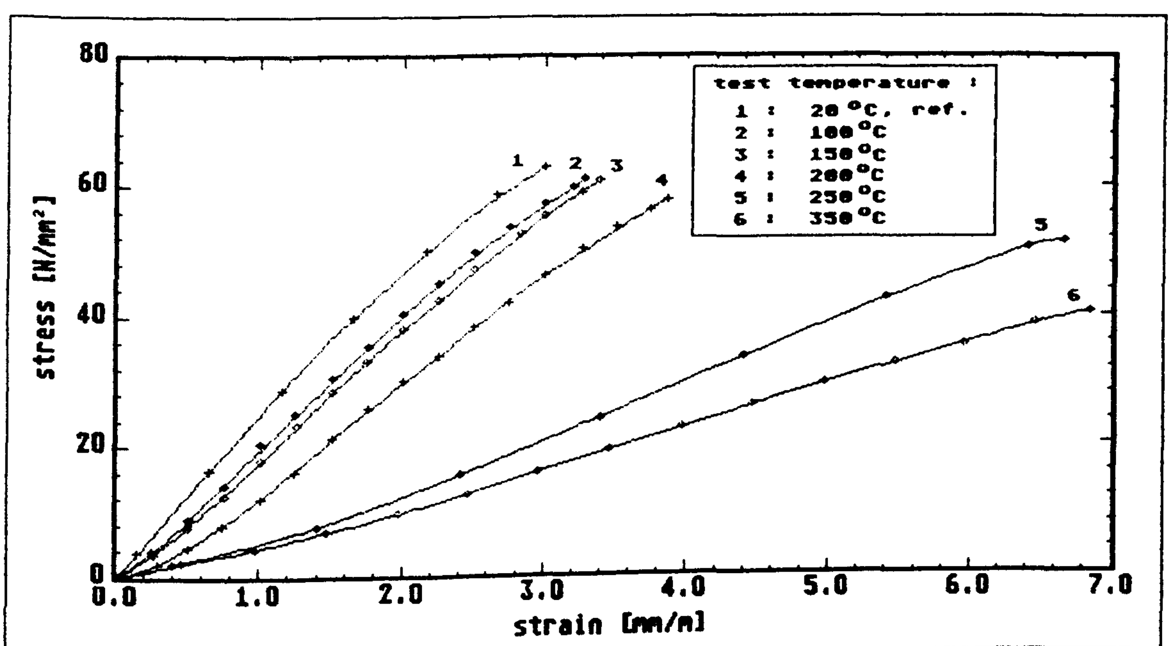


Fig. 16: Residual σ-ϵ-relationships measured with HS-LWA-concrete specimens of contractor 2.

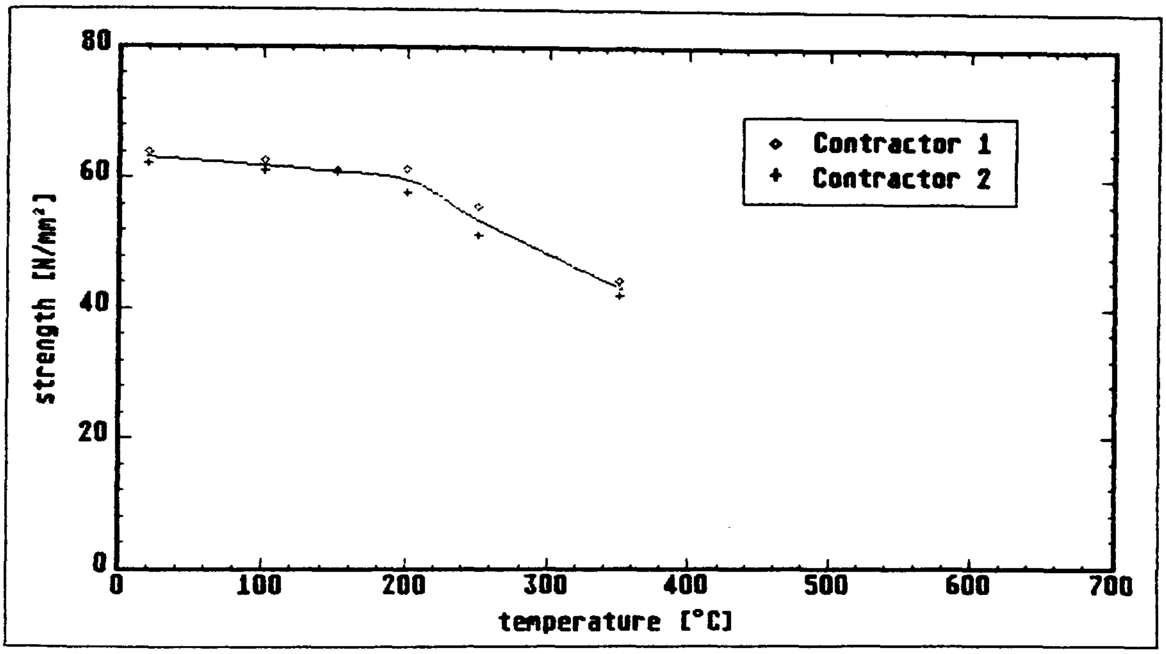


Fig. 17: Residual compressive strength of HS-LWA-concrete after heat exposure.

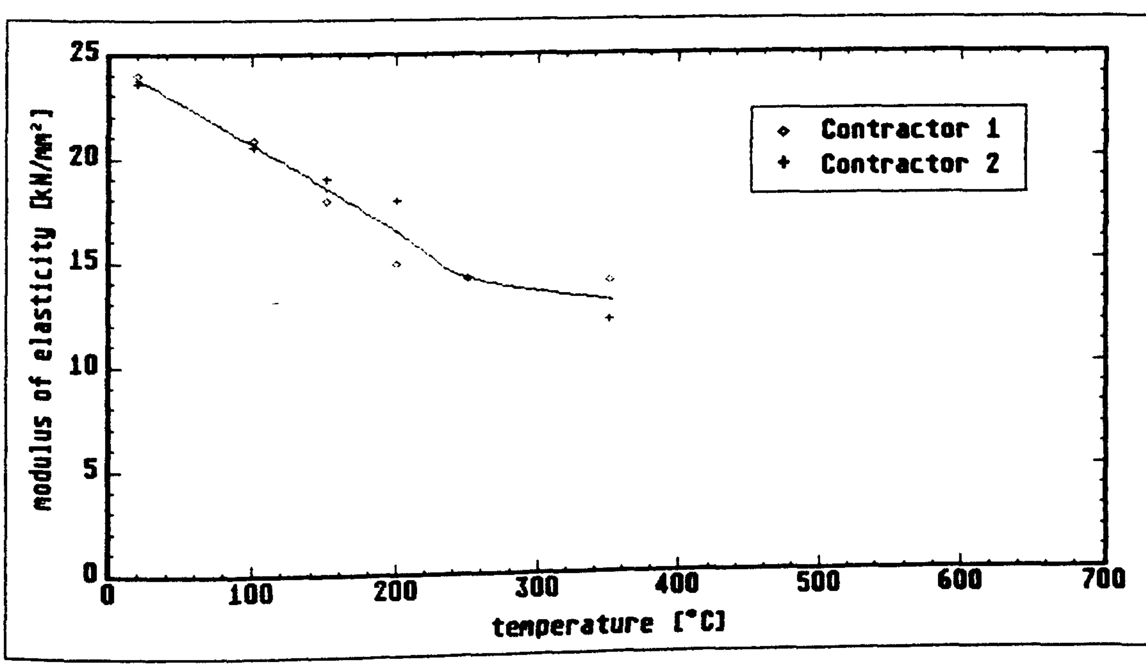


Fig. 18: Residual modulus of elasticity of HS-LWA concrete after heat exposure.

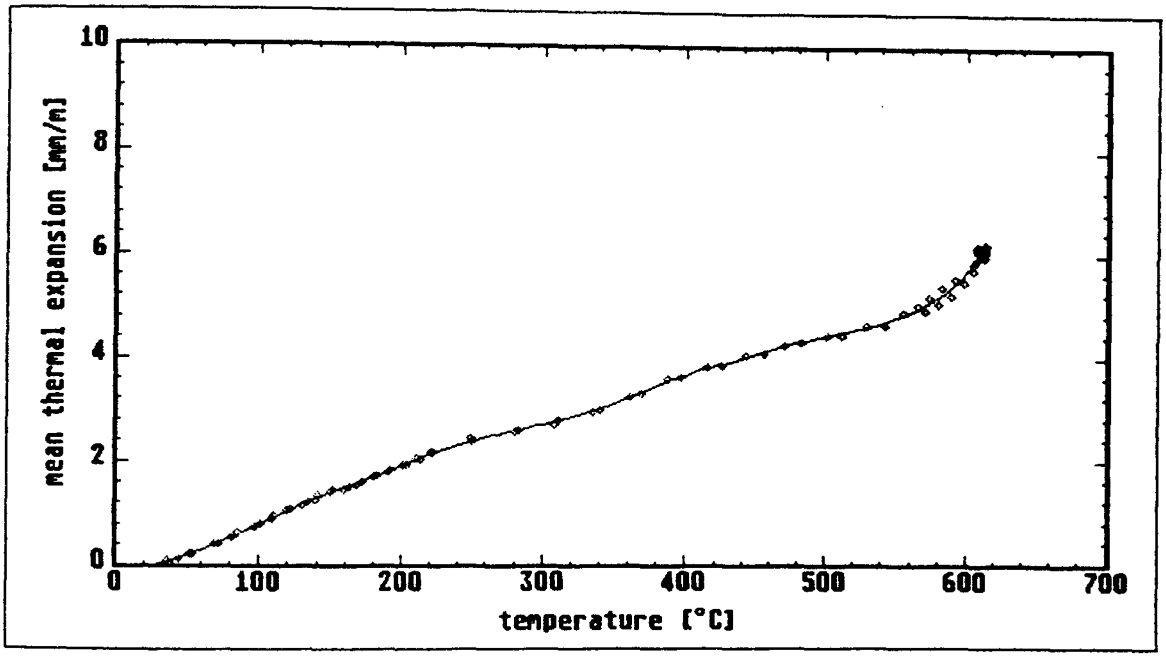


Fig. 19: Mean thermal expansion of HS-LWA concrete specimens of contractor 1.

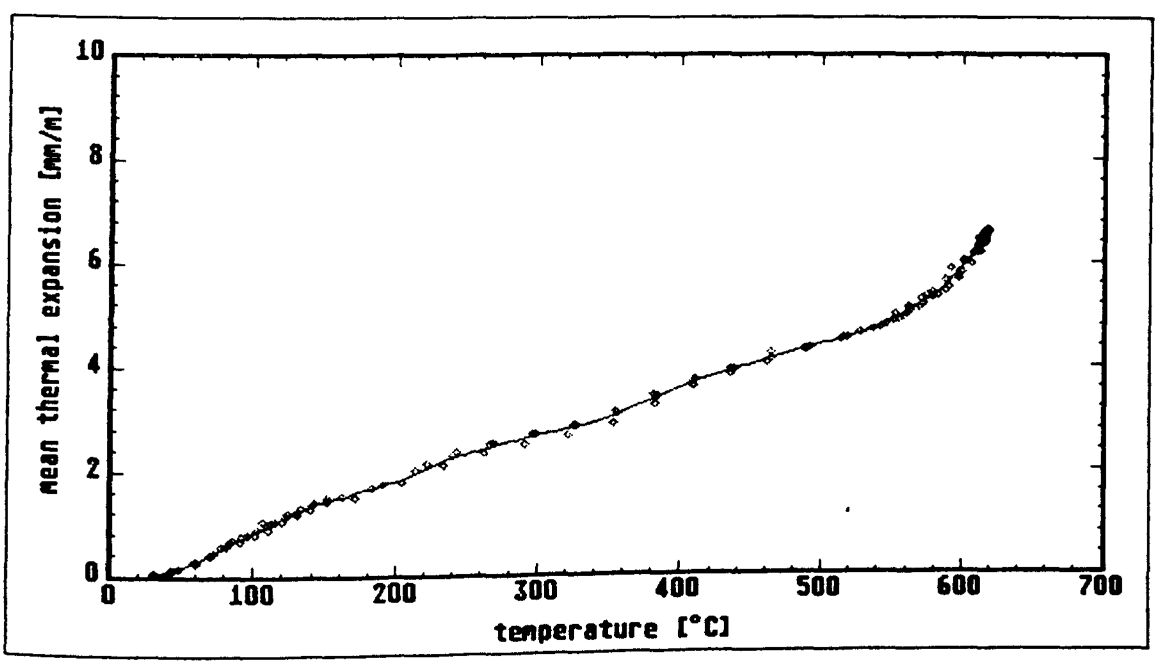


Fig. 20: Mean thermal expansion of HS-LWA-concrete specimens of contractor 2.

Bearbeitungs-Nr. 8762/8762

Antragsteller: Dr. Diederichs

Antrag vom: 10. 10. 91

Versuchsmaterial: 2 Leichtbetonbohrkerne
Ø = cm, H = cm

Eingang: 10. 10. 91

Kennzeichnung: siehe unten

Prüfung:	geprüft am	Prüfer
Abmessungen, Masse	14.10.91	Fr
Rohdichte	14.10.91	Fr
Druckfestigkeit	15.10.91	Fr
Feuchtigkeitsgehalt		

Nr.	Bez.	Ø (mm)	Höhe (mm)	Masse lufttrck. (Kg)	R lufttrck. (Kg/m³)	Höhe nach dem Abgleichen (mm)	H/Ø	FU (KN)	A (mm²)	β_{Dr} (N/mm²)
1	HP1	84,0	300,7	3,227	1937	302,0	3,60	346,0	5541,77	62,4
2	HP2	84,0	300,4	3,217	1932	303,1	3,61	364,5	5541,77	65,8
					1935					64,1

Feuchtigkeitsgehalt (105° C)

Nr.	Bez.	Masse lufttrck. (Kg)	M 1 (Kg)	M 2 (Kg)	M 3 (Kg)	M 4 (Kg)	M 5 (Kg)	Masse trocken (Kg)	Masse Differenz (g)	Feuchtigkeit Masse %
1	HP1	1,409	1,324	1,310	1,303	1,297	1,295	1,295	114	8,80
2	HP2	1,359	1,283	1,268	1,259	1,252	1,250	1,250	109	8,72
									$\bar{x}$ =	8,76

Antragsteller: Dr. Diederichs

Antrag vom: 05. 11. 91

Versuchsmaterial: 2 Leichtbetonzylinder

Ø = 8 cm, H = 30 cm

Eingang: 06. 11. 91

Kennzeichnung: HP 2-1, HP 2-2

Bearbeitungs-Nr. 8762 / 8762

Prüfung:	geprüft am	Prüfer
Abmessungen, Masse	06.11.91	Fr
Rohdichte	06.11.91	Fr
E-Mo Druckfestigkeit	07.11.91	Fr
Feuchtigkeitsgehalt	21.11.91	Fr

BETONPRÜFUNGEN

Art, Anzahl und Abmessungen (cm) der Prüfkörper	Würfel	Prismen	Balken	Zylinder	Platten
	10x10x10	15x15x70	10x15x70	d15;h 30	20x20x12
	15x15x15	20x20x90	15x15x70	d15;h 35	
	20x20x20			d20;h 80	

Zylinder: Druckfestigkeit - Spaltzugfestigkeit - E-Modul - Schwinden - Kriechen

HP 2-1	12.07.91	07.11.91	118			30,04	8,00	2891	1,915	306,8	
HP 2-2						30,03	7,99	2918	1,938	318,0	
									1,927		62,2

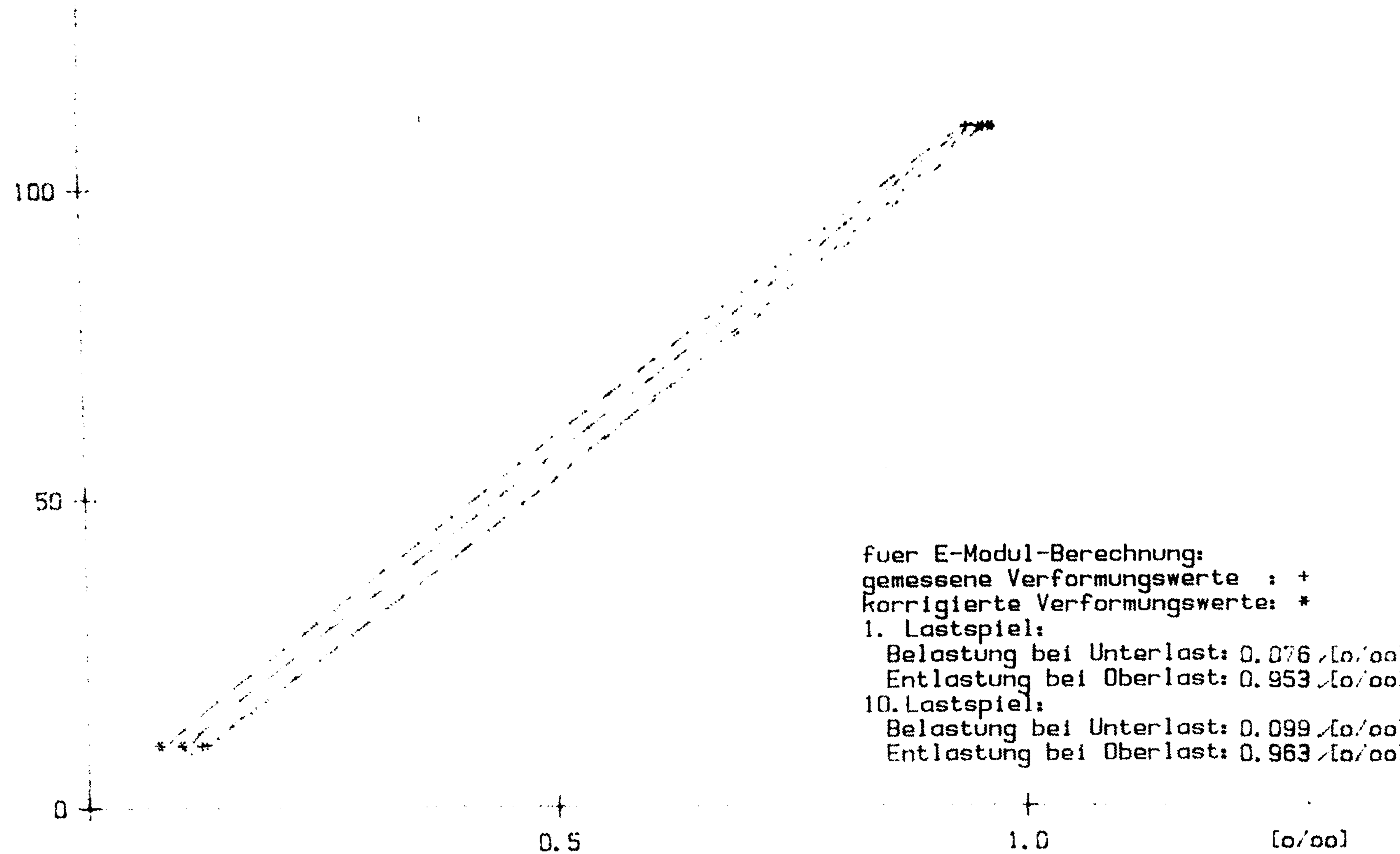
+) Prüfung im Alter von (Tg)
Prüfung bei Versuchsbeginn (VB)
Prüfung bei Versuchsdurchführung (VD)
Prüfung bei Versuchsende (VE)
Prüfung nach Angabe (Angabe eintr.)

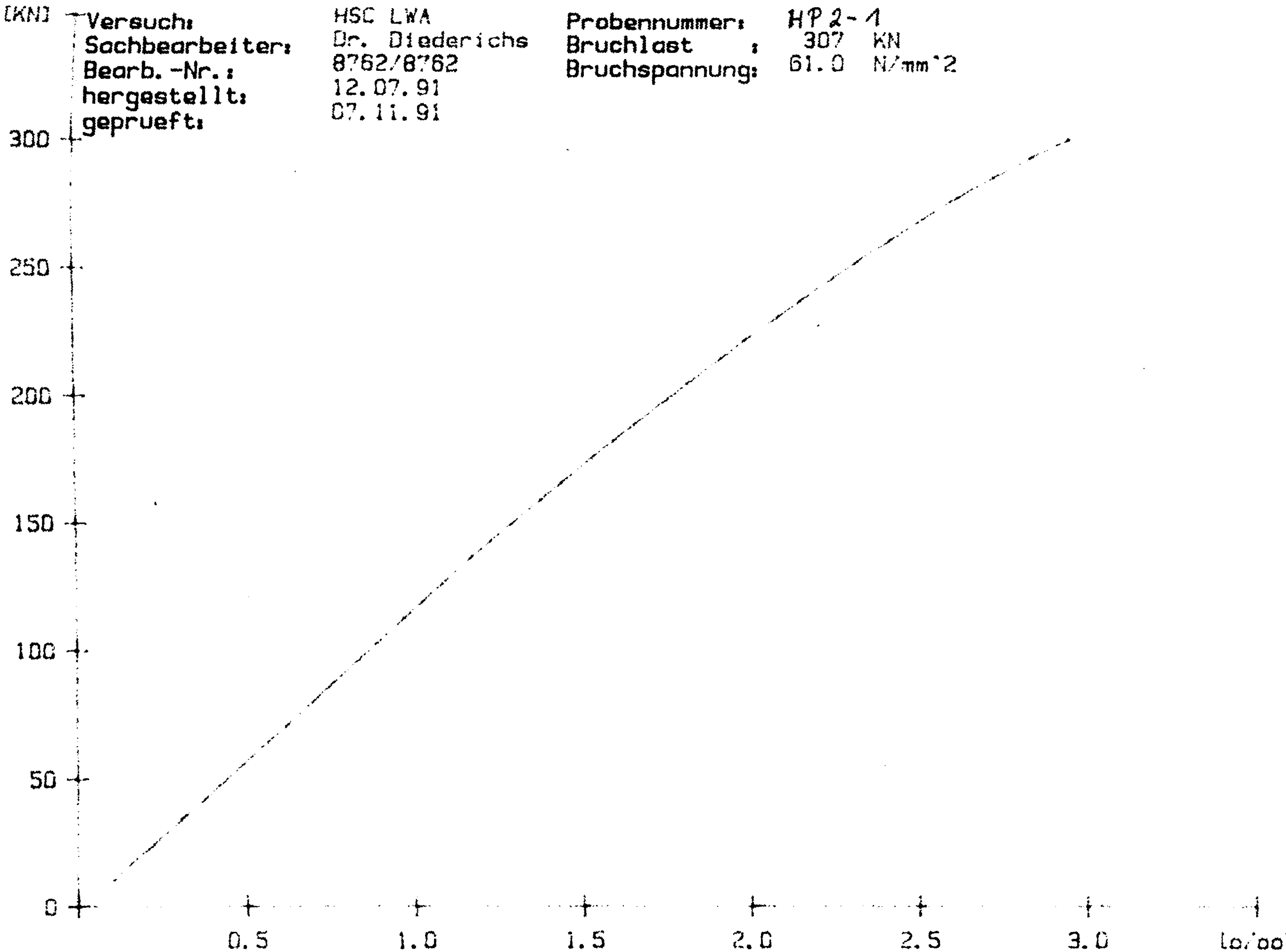
Prüfmaschine: W+B 2000 kN
Prüfer: Fr

Nr.	Bez.	Masse luftfeucht. (g)	M1 (g)	M2 (g)	M3 (g)	M4 (g)	M5 (g)	Masse trocken (g)	Masse Differenz (g)	Masse %		
1	HP 2-1	2330	2267	2248	2157	2146	2145	2145	185	8,62		
2	HP 2-2	2725	2610	2528	2514	2499	2497	2497	228	9,13		
Mi	—	—	—	—	—	—	—	—	—	8,88		

Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 07.11.91

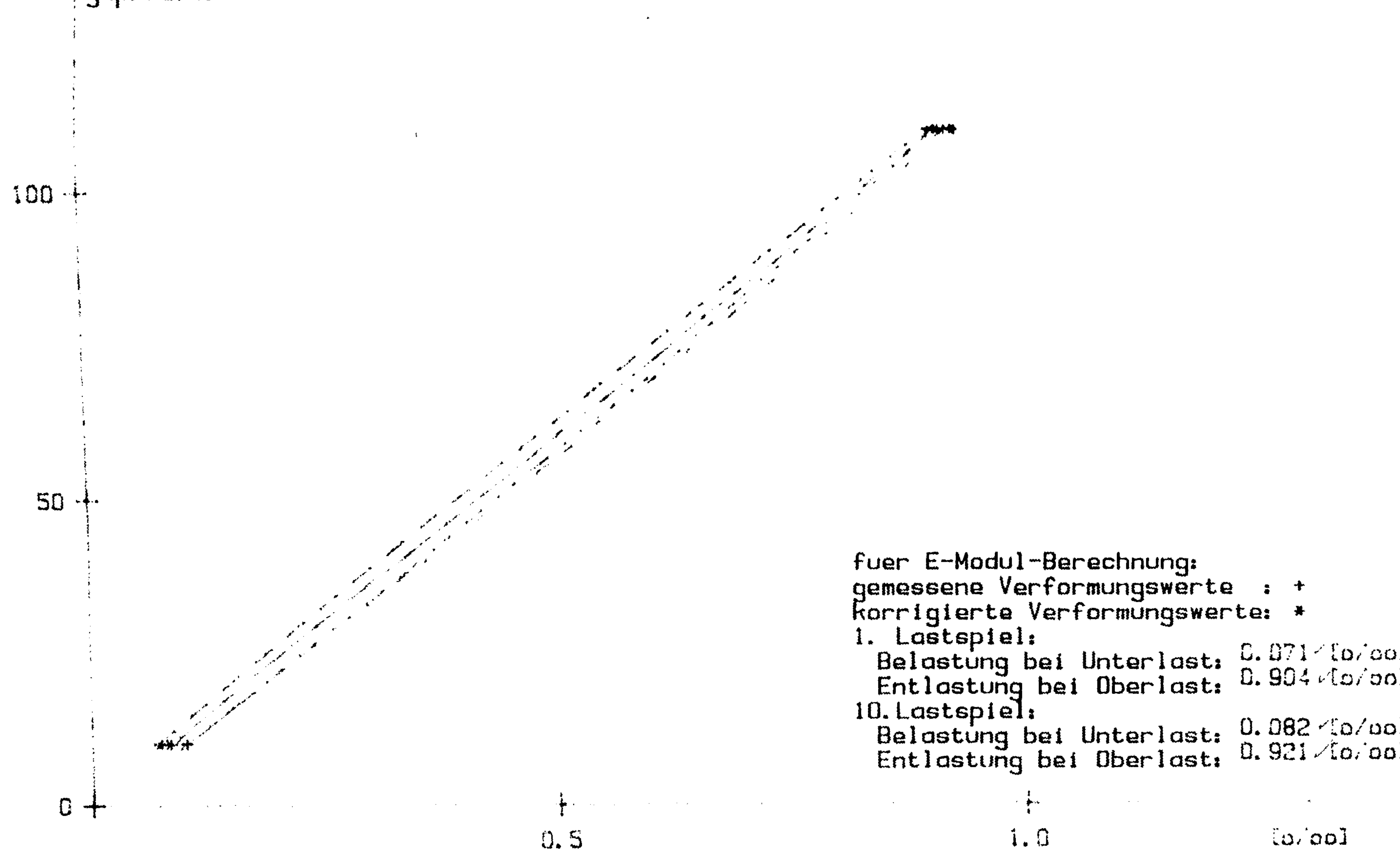
Probennummer: HP2-1
1. Lastspiel: — — — —
10. Lastspiel: ————
Unterlast : 10 KN
Oberlast : 110 KN

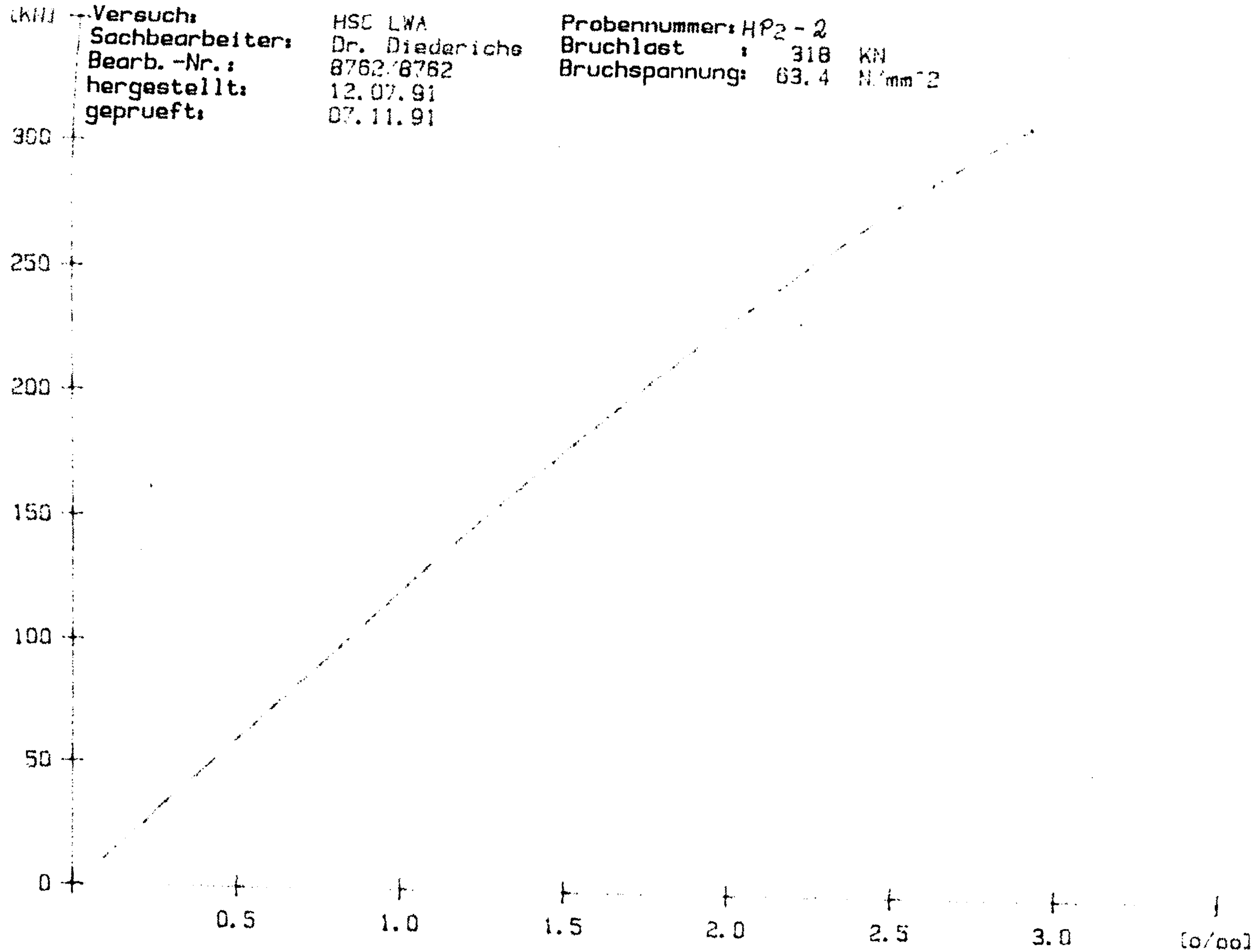



[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 07.11.91
Probennummer: HP2-1
Bruchlast : 307 KN
Bruchspannung: 61.0 N/mm^2
300
250
200
150
100
50
0
0.5
1.0
1.5
2.0
2.5
3.0
[o/oo]

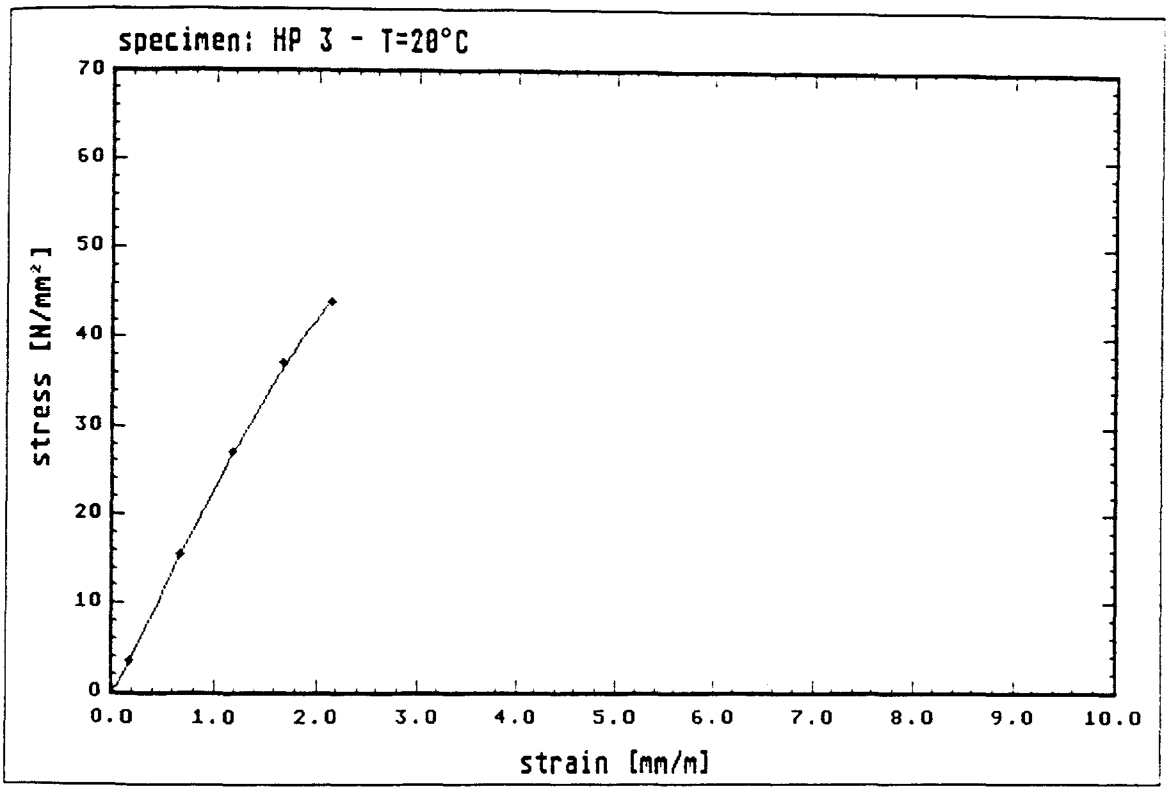
- A 4 -

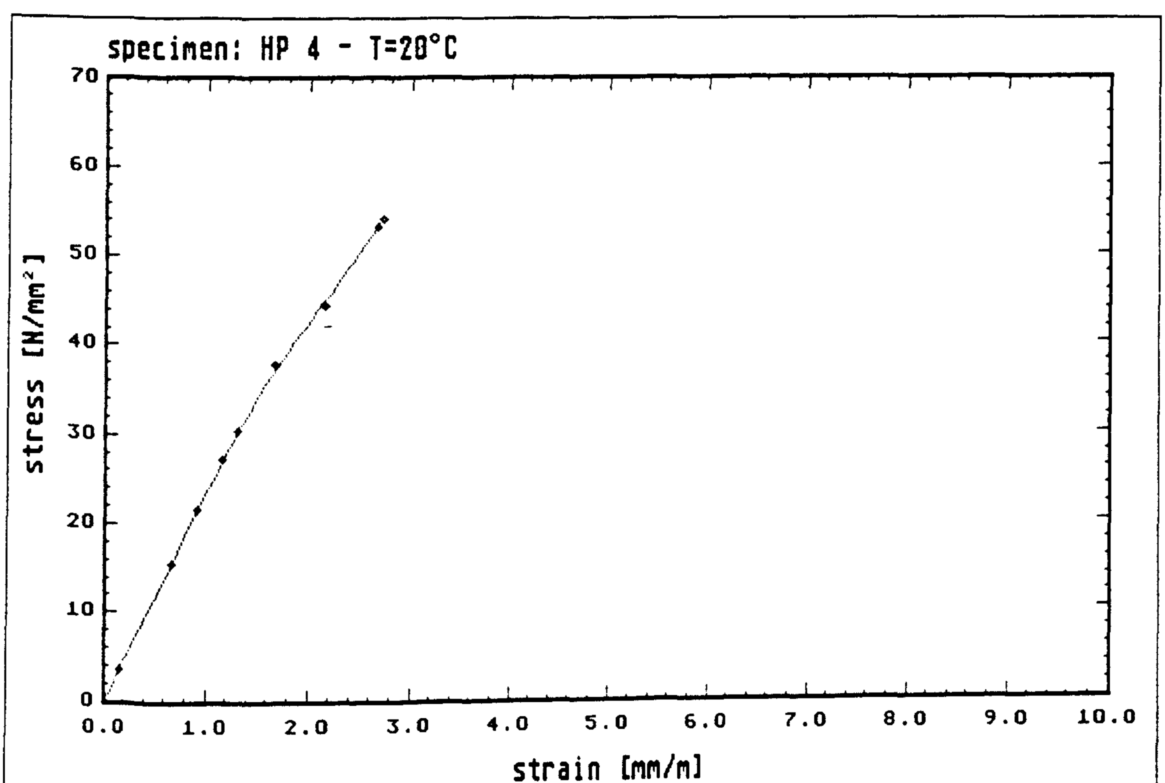
Versuch:	HSC LWA	Probennummer:	HP2-2
Sachbearbeiter:	Dr. Diederichs	1. Lastspiel:	— — — —
Bearb.-Nr.:	8762/8762	10. Lastspiel:	— — — —
hergestellt:	12.07.91	Unterlast :	10 KN
geprueft:	07.11.91	Oberlast :	110 KN

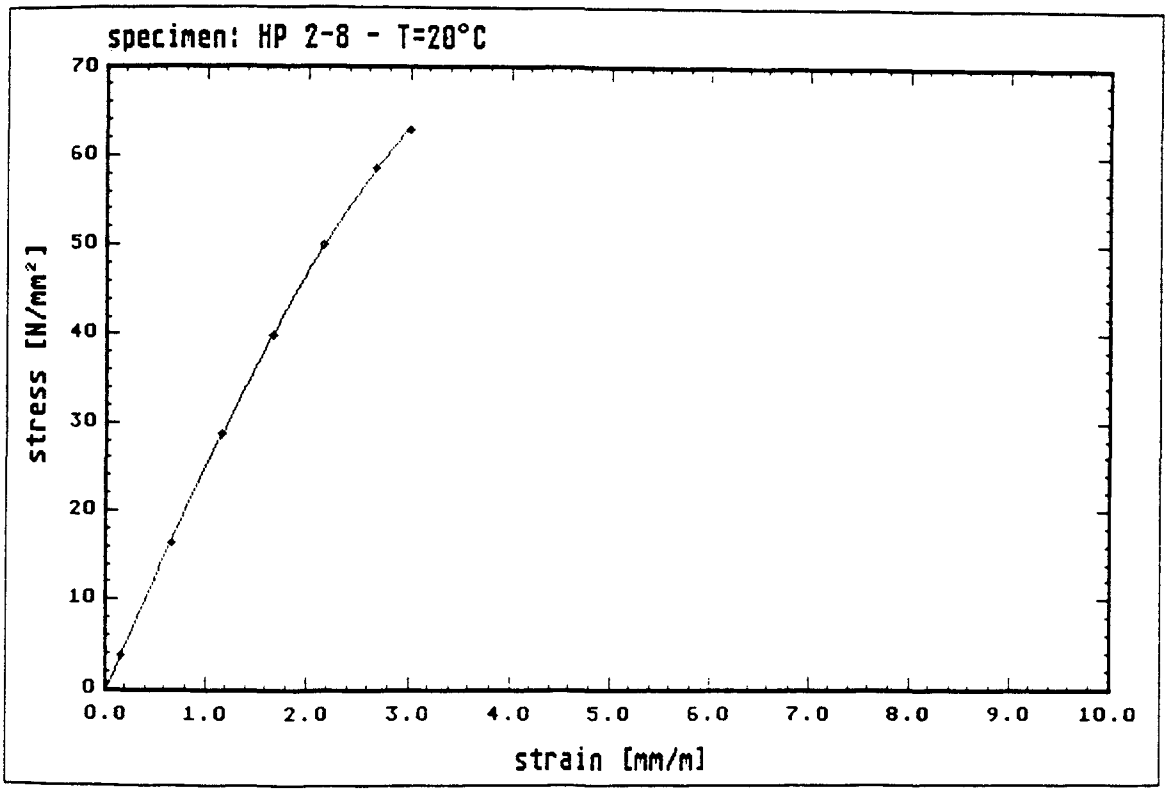


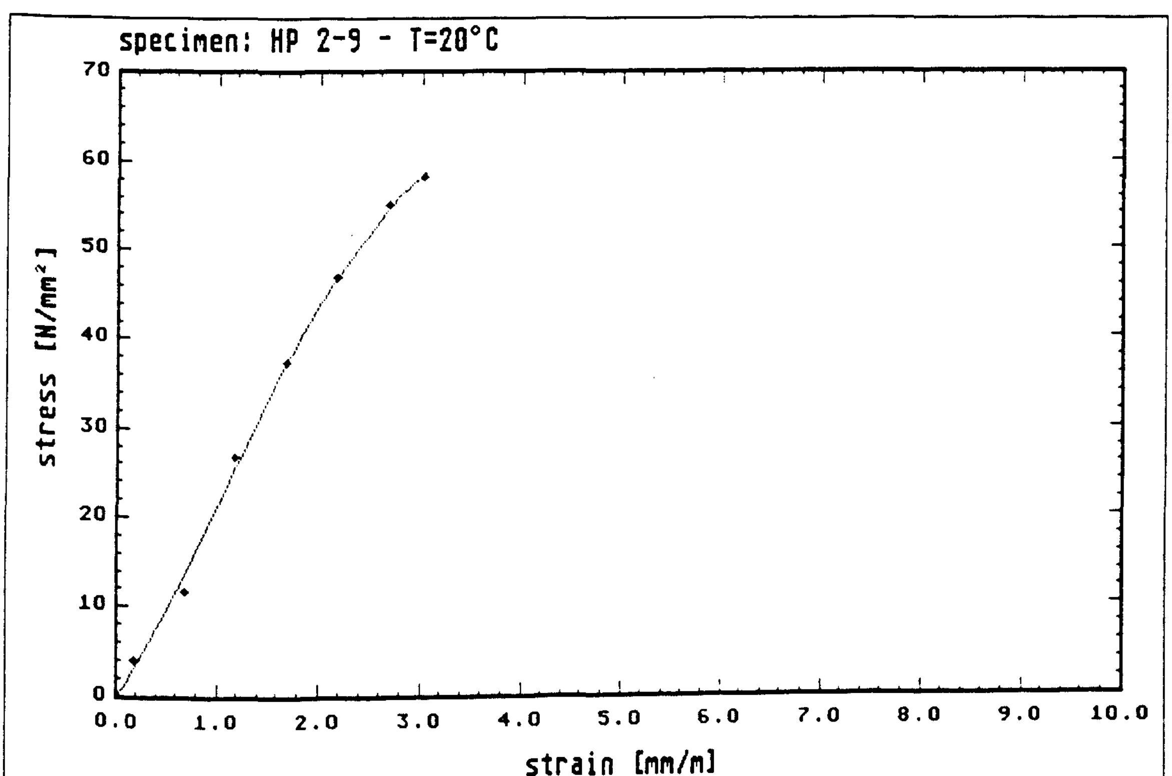

Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 07.11.91
Probennummer: HP2 - 2
Bruchlast : 318 KN
Bruchspannung: 63.4 N/mm^2
[kN]
0
50
100
150
200
250
300
0.5
1.0
1.5
2.0
2.5
3.0
[o/oo]

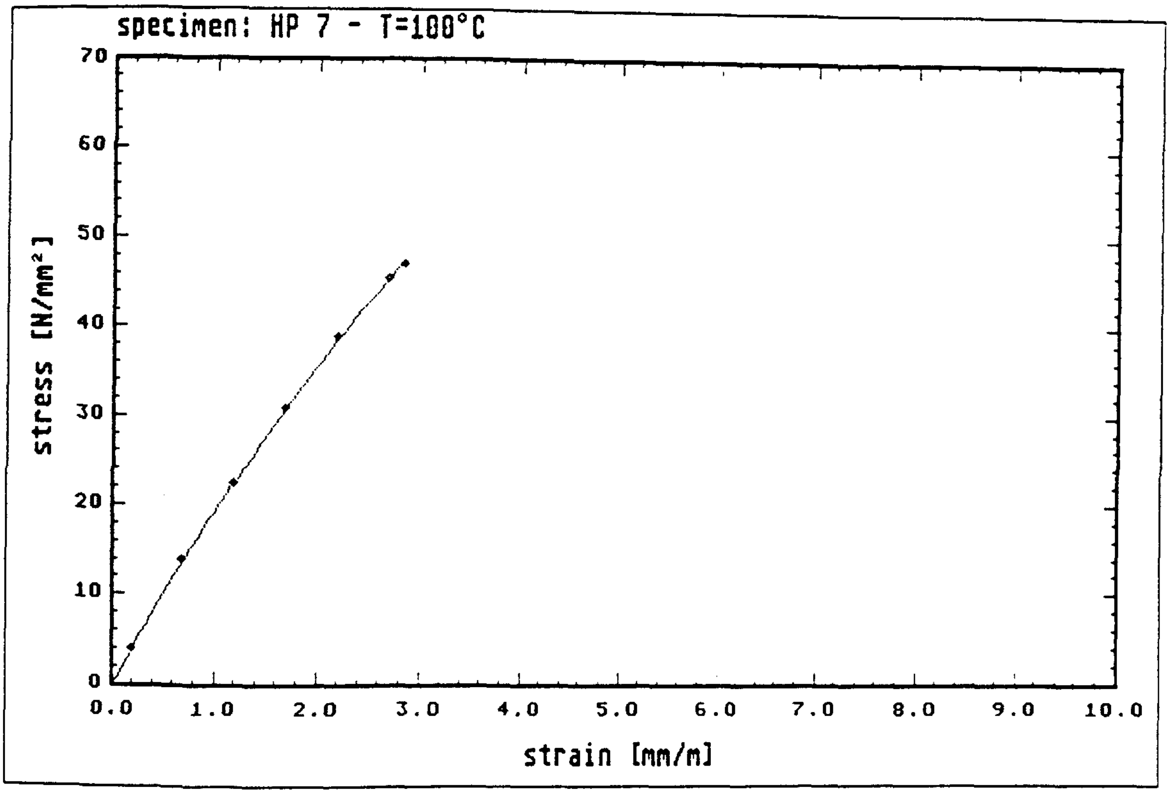
Conoco - Temperaturversuche

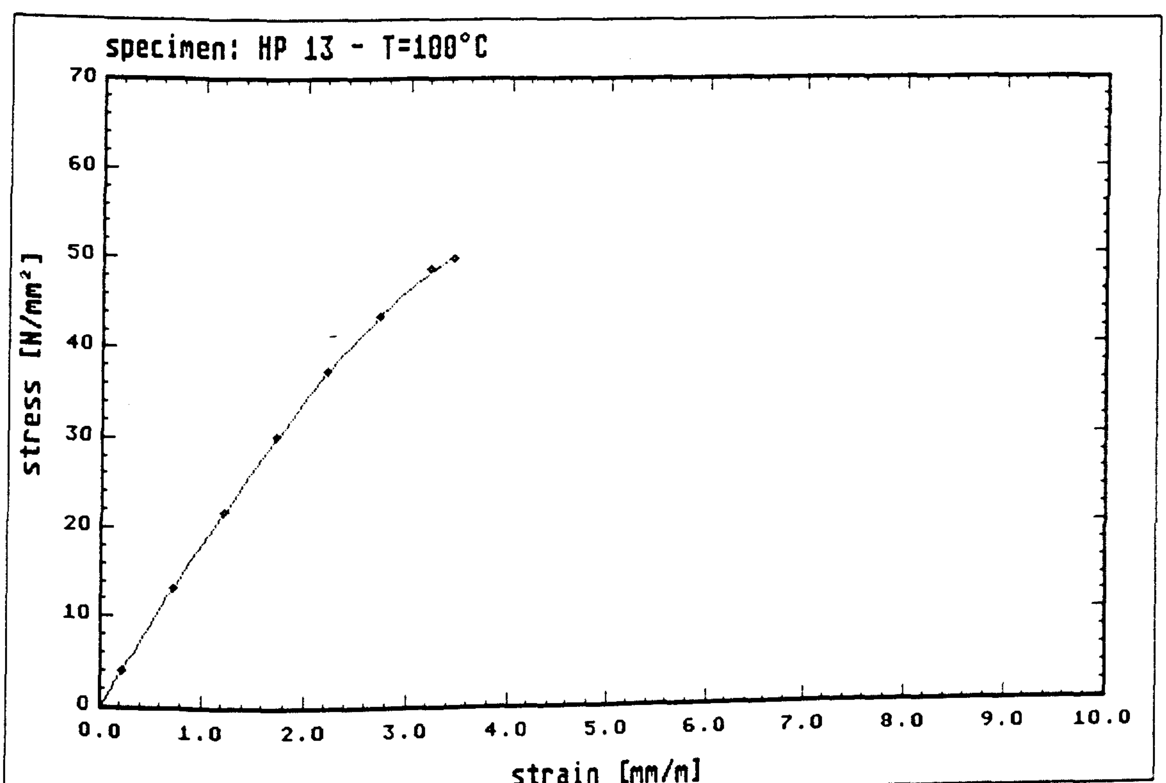


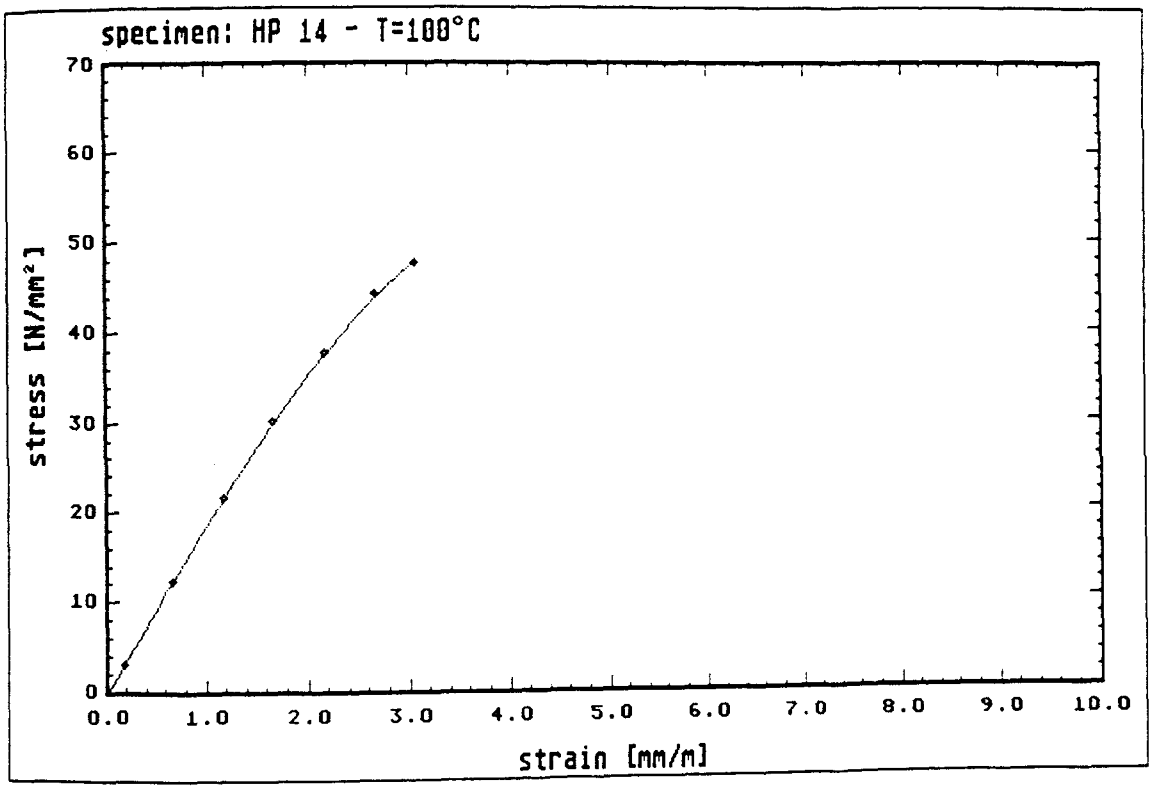


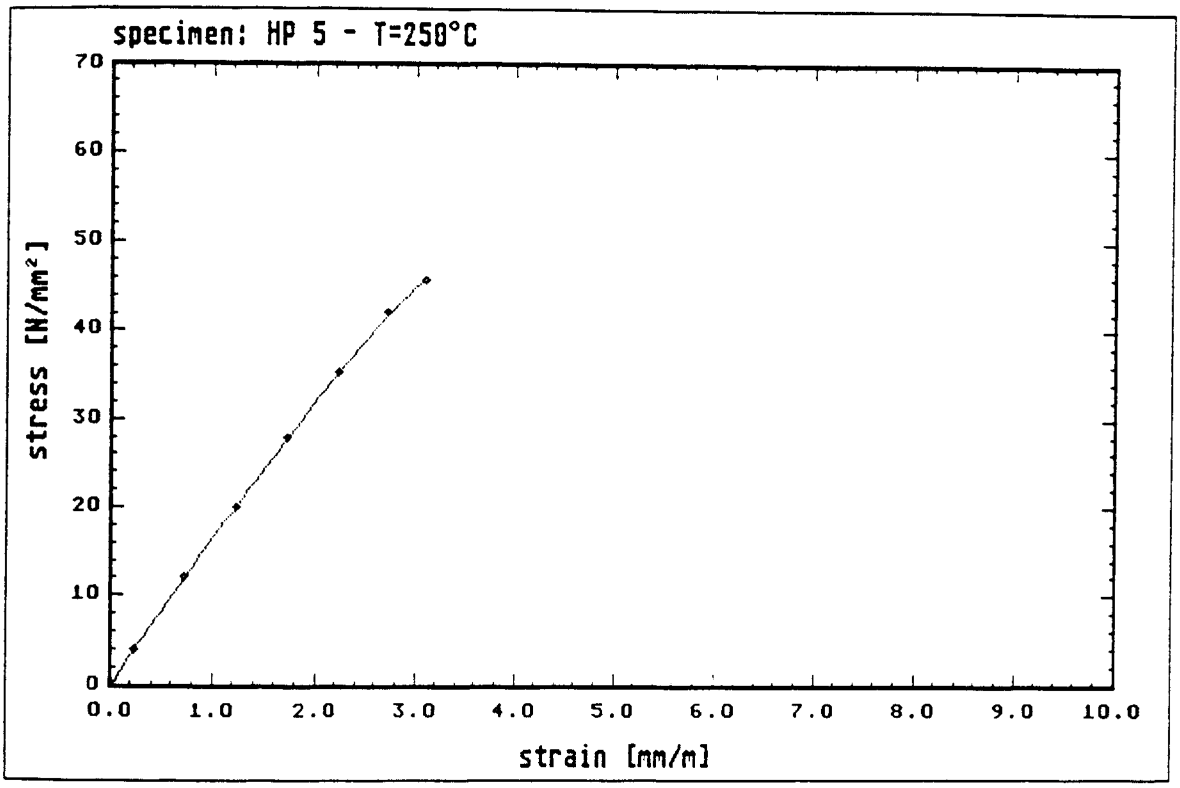

specimen: HP 2-8 - T=20°C
stress [N/mm²]
strain [mm/m]
70
60
50
40
30
20
10
0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

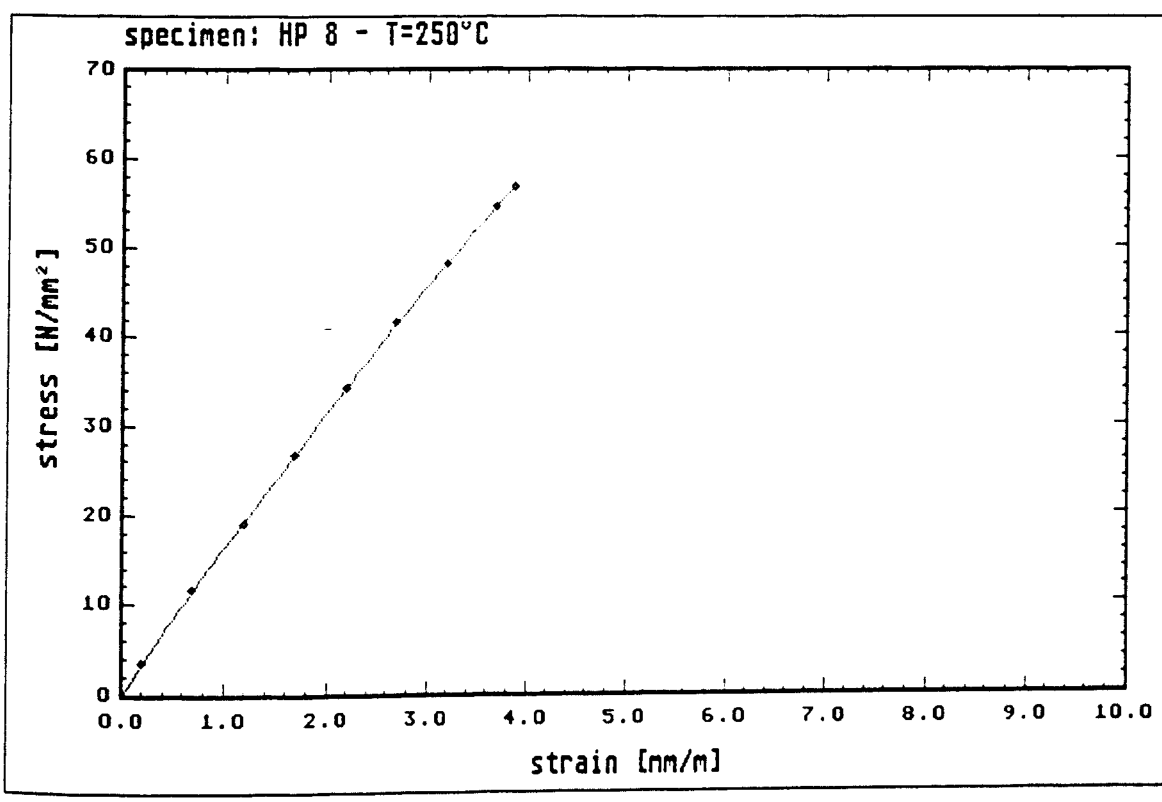

specimen: HP 2-9 - T=20°C
stress [N/mm²]
strain [mm/m]
70
60
50
40
30
20
10
0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

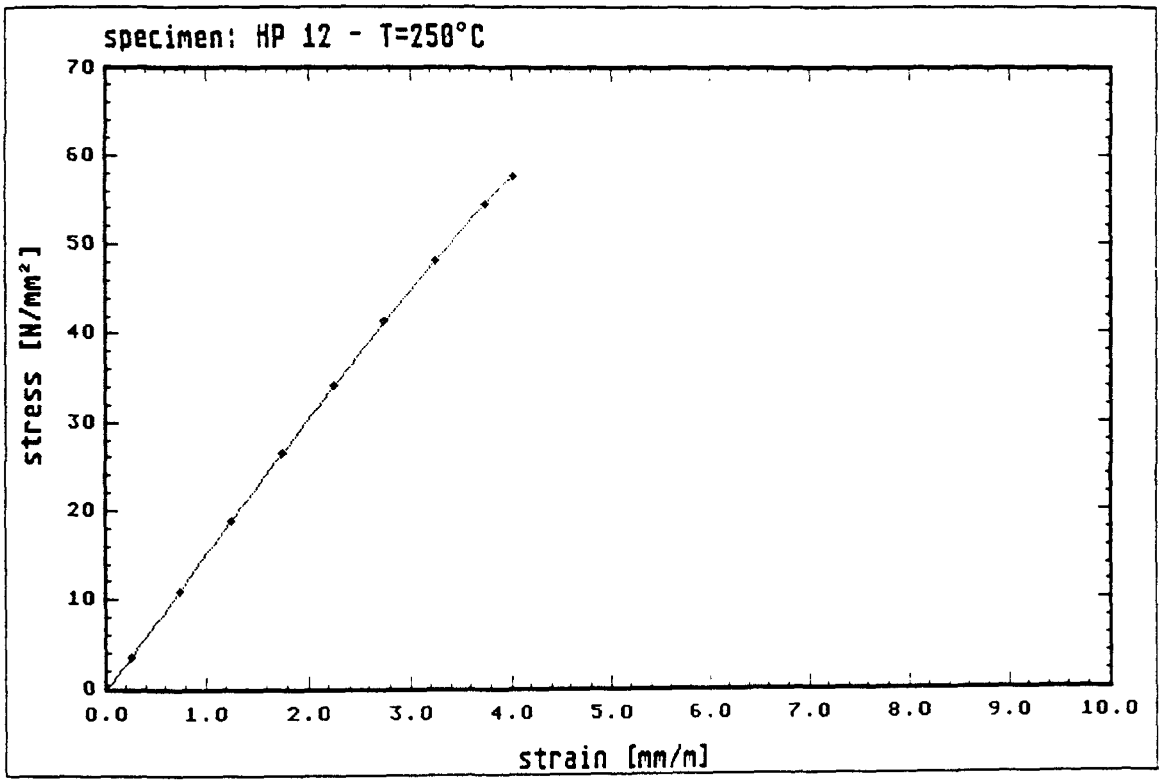

specimen: HP 7 - T=100°C
stress [N/mm²]
strain [mm/m]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

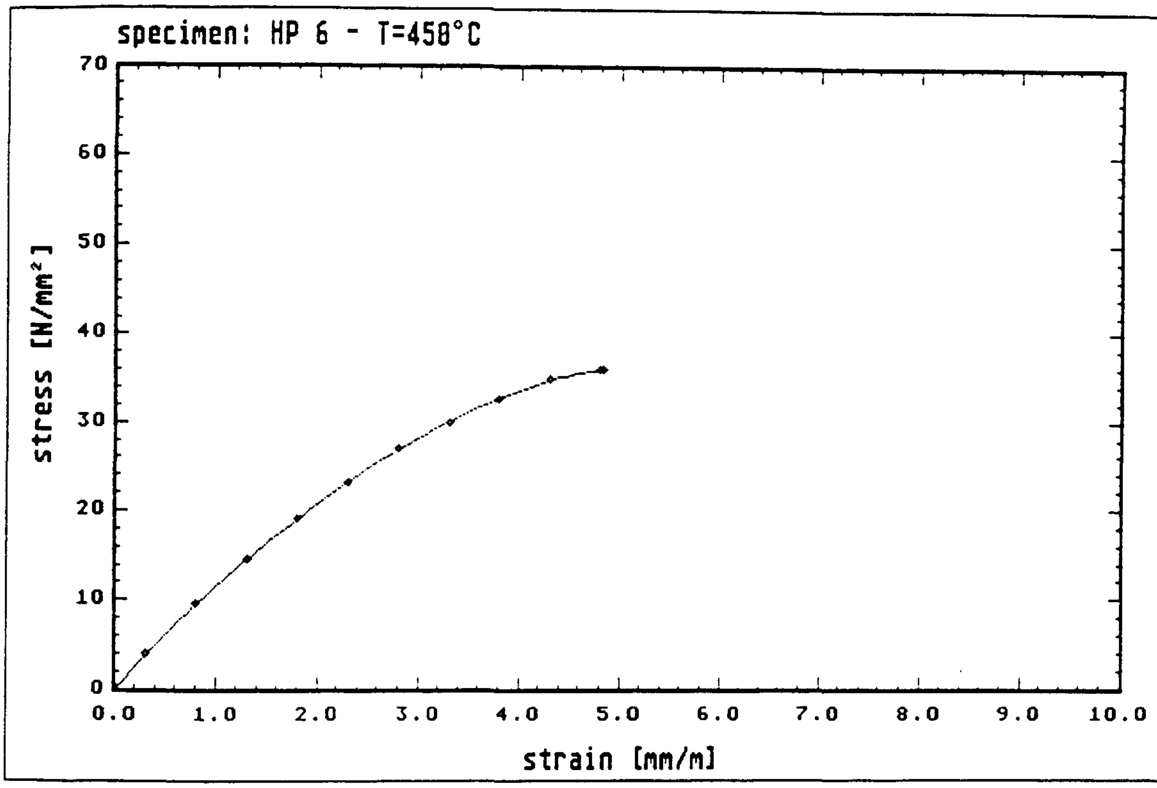

specimen: HP 13 - T=100°C
stress [N/mm²]
strain [mm/m]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

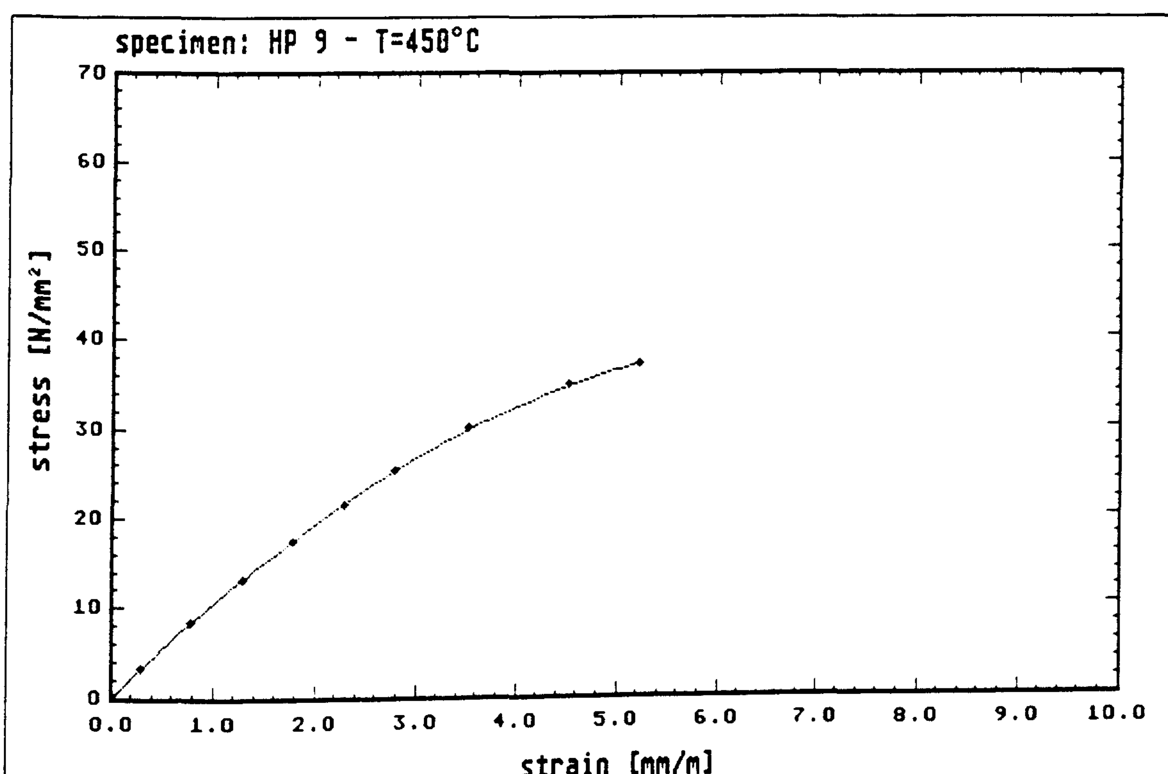

specimen: HP 14 - T=100°C
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

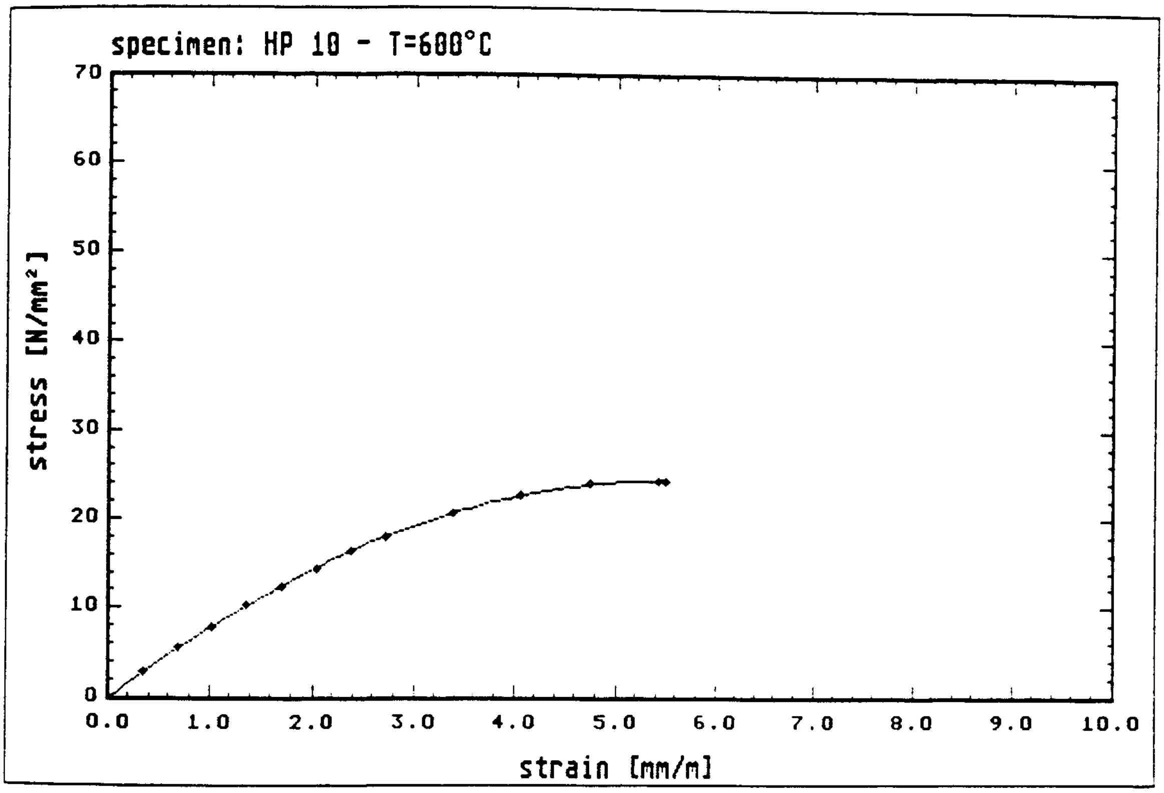

specimen: HP 5 - T=250°C
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

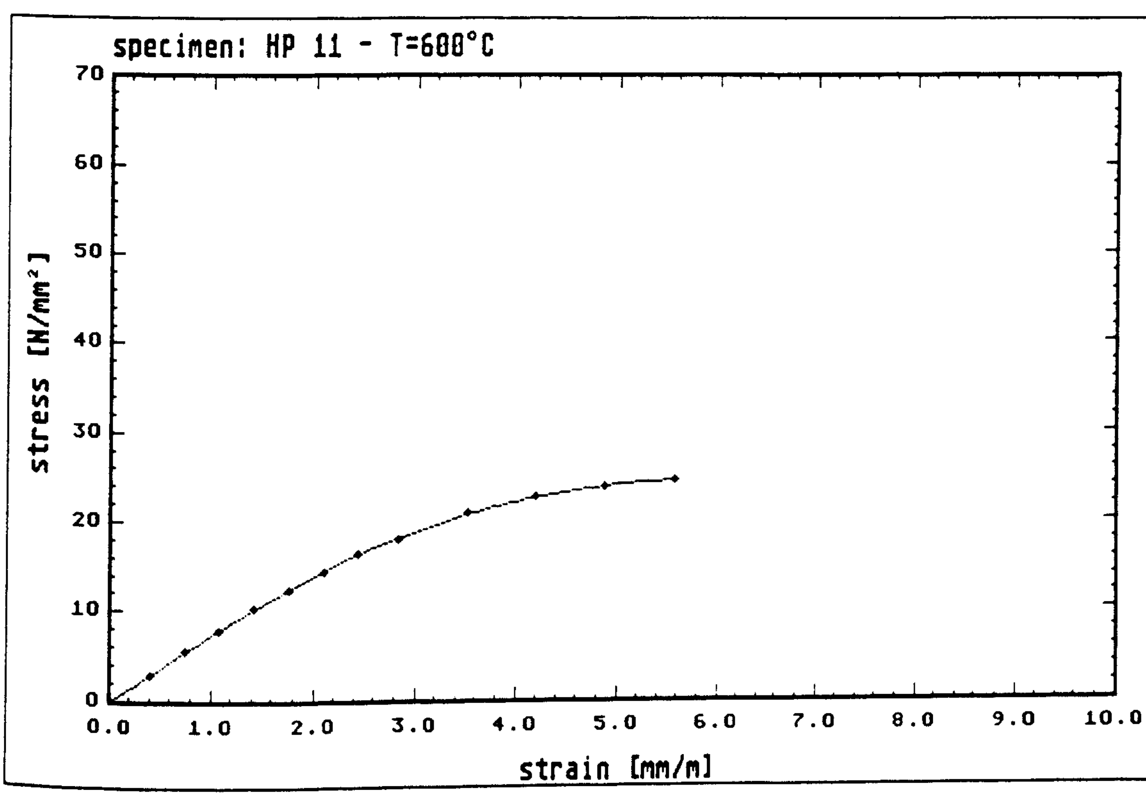

specimen: HP 8 - T=250°C
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

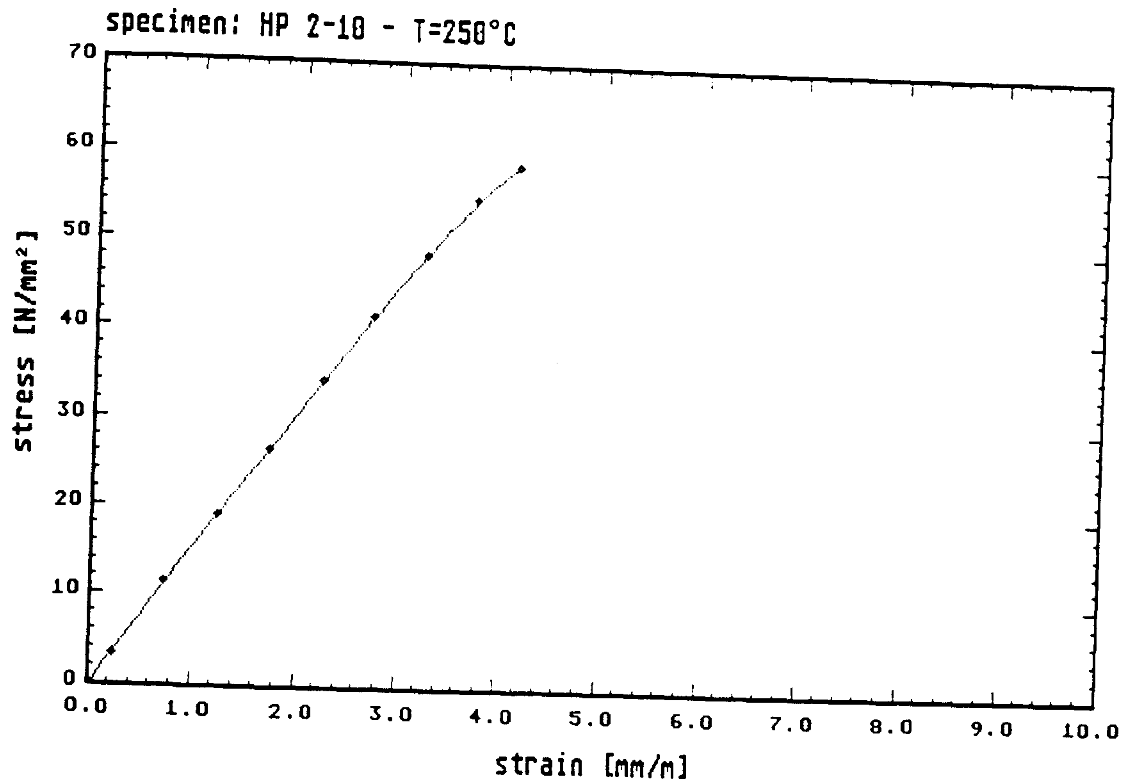

specimen: HP 12 - T=250°C
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

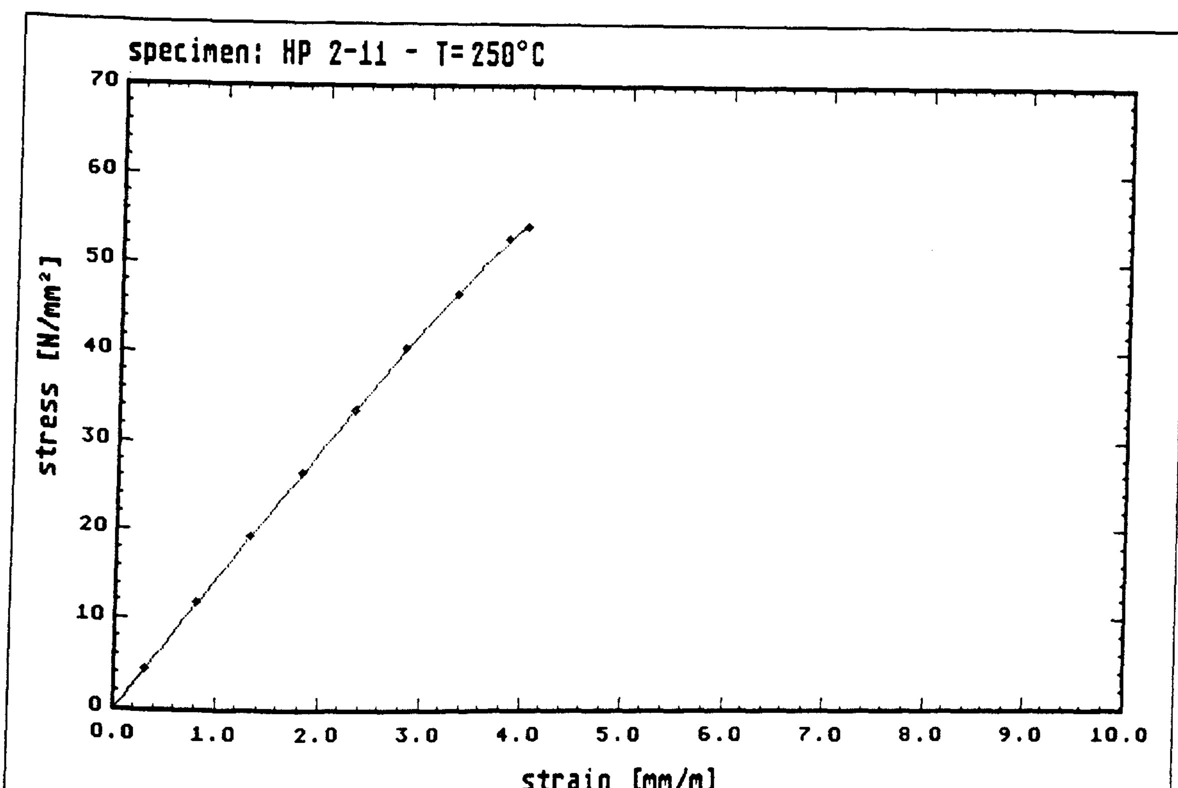

specimen: HP 6 - T=450°C
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

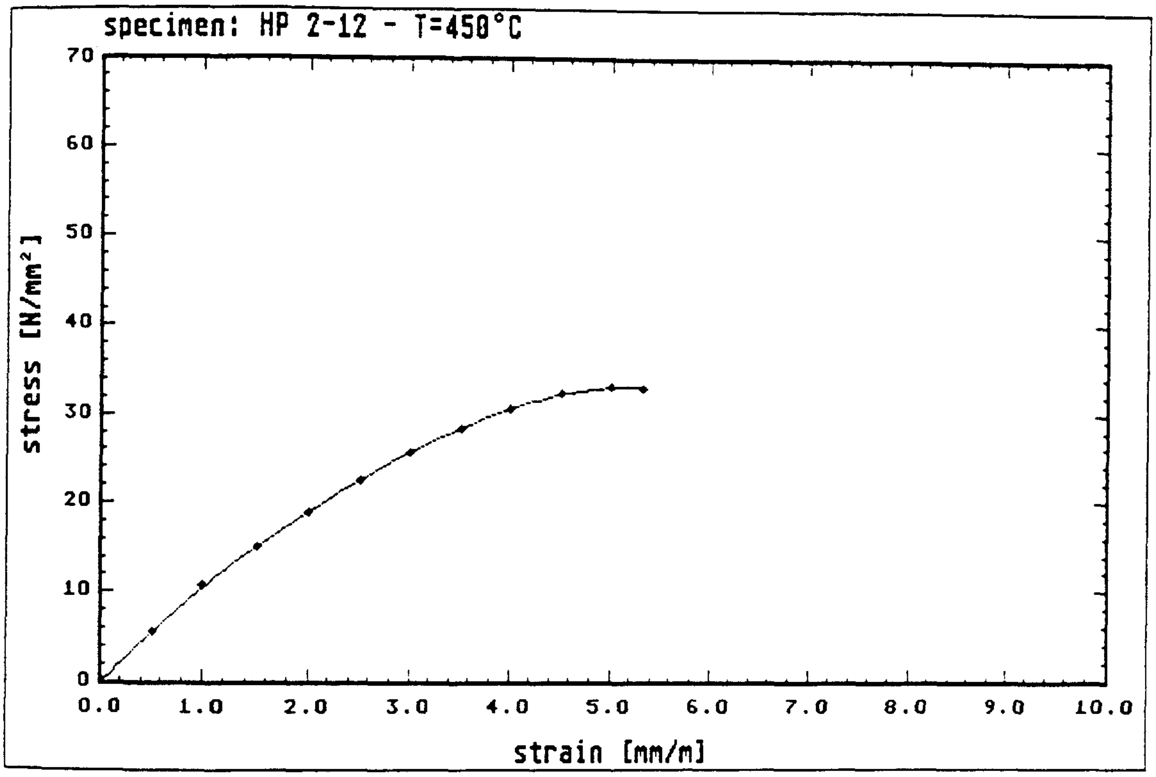

specimen: HP 9 - T=450°C
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

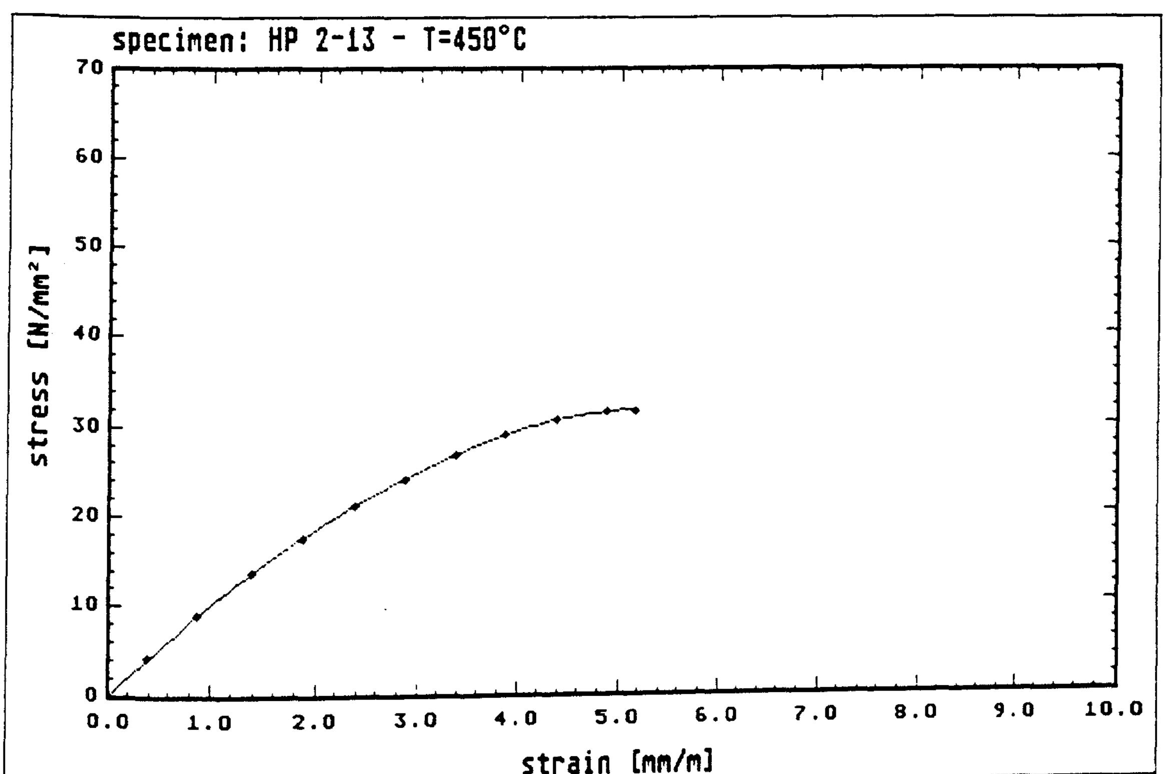

specimen: HP 10 - T=600°C
stress [N/mm²]
strain [mm/m]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

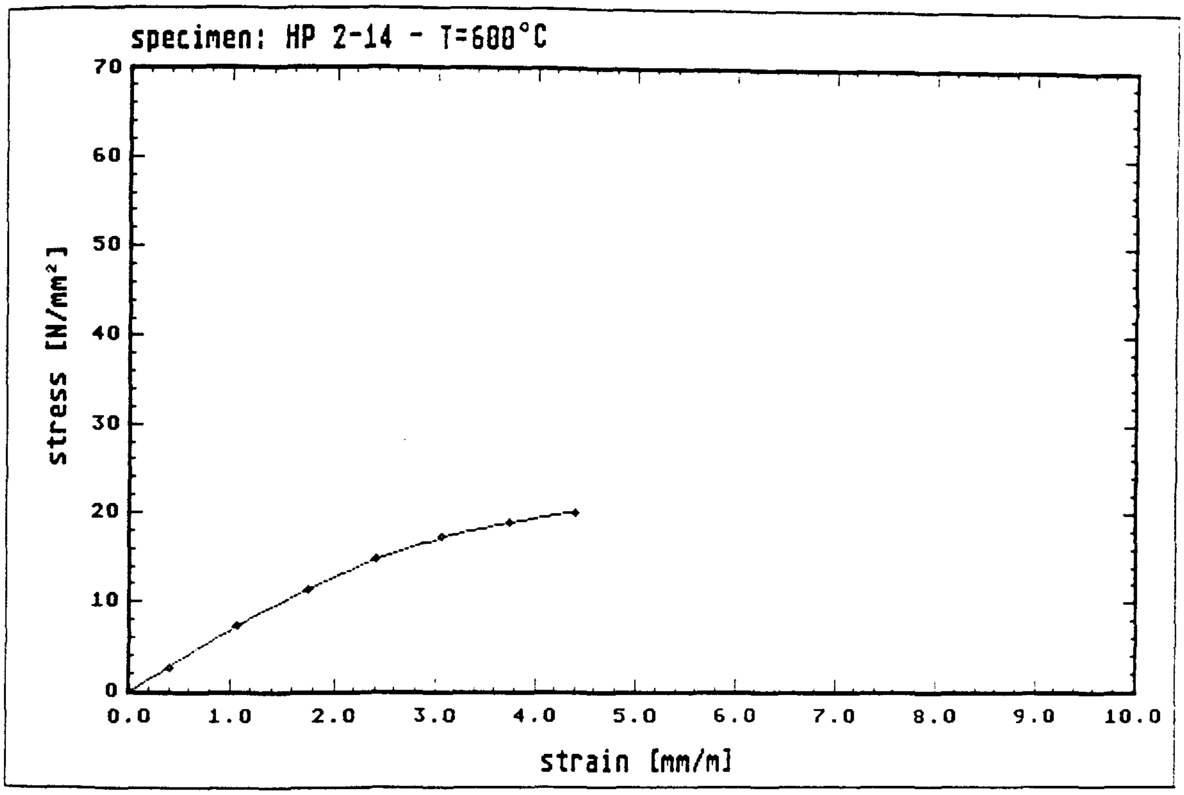

specimen: HP 11 - T=600°C
stress [N/mm²]
strain [mm/m]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

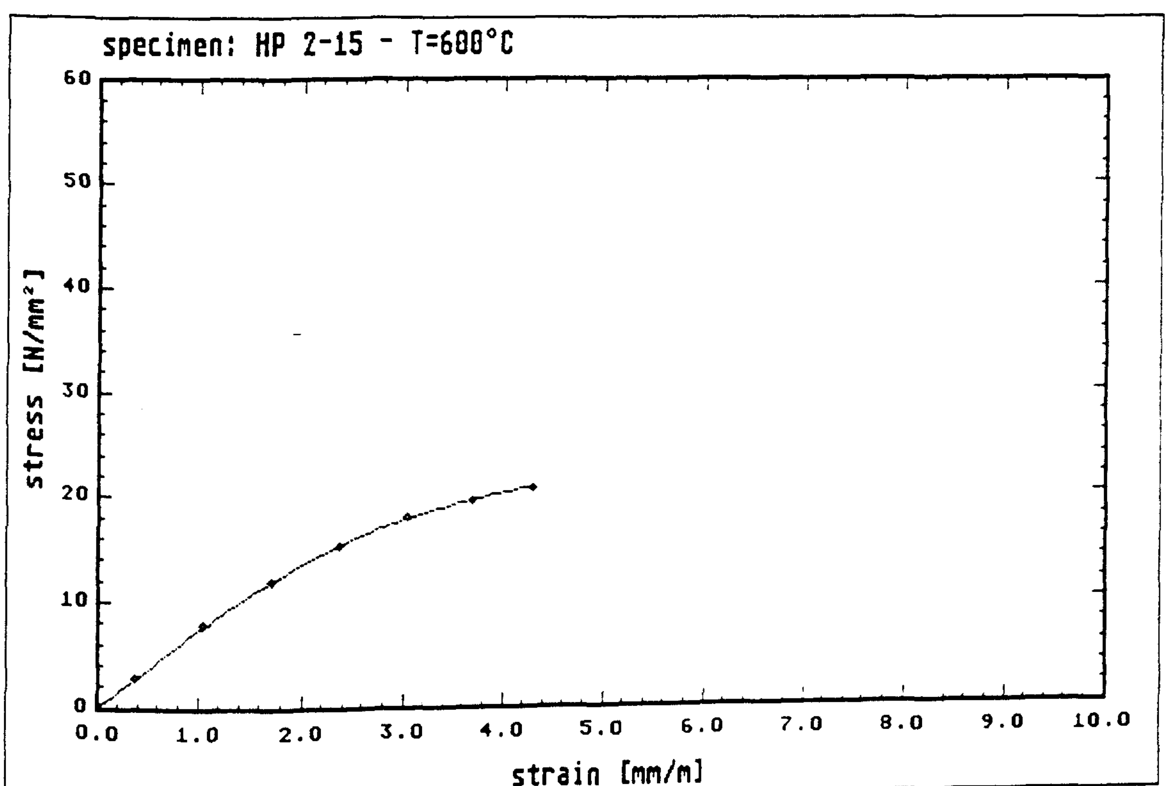

specimen: HP 2-10 - T=250°C
stress [N/mm²]
strain [mm/m]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

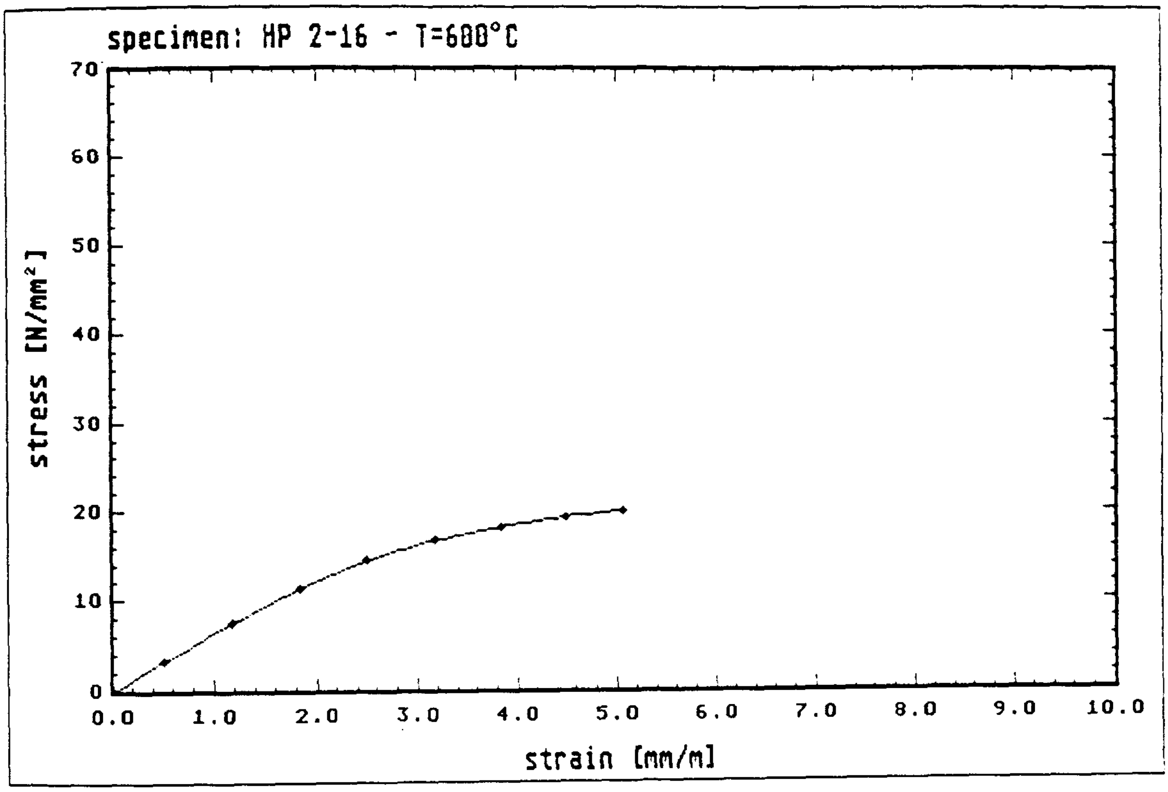

specimen: HP 2-11 - T=250°C
stress [N/mm²]
strain [mm/m]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0

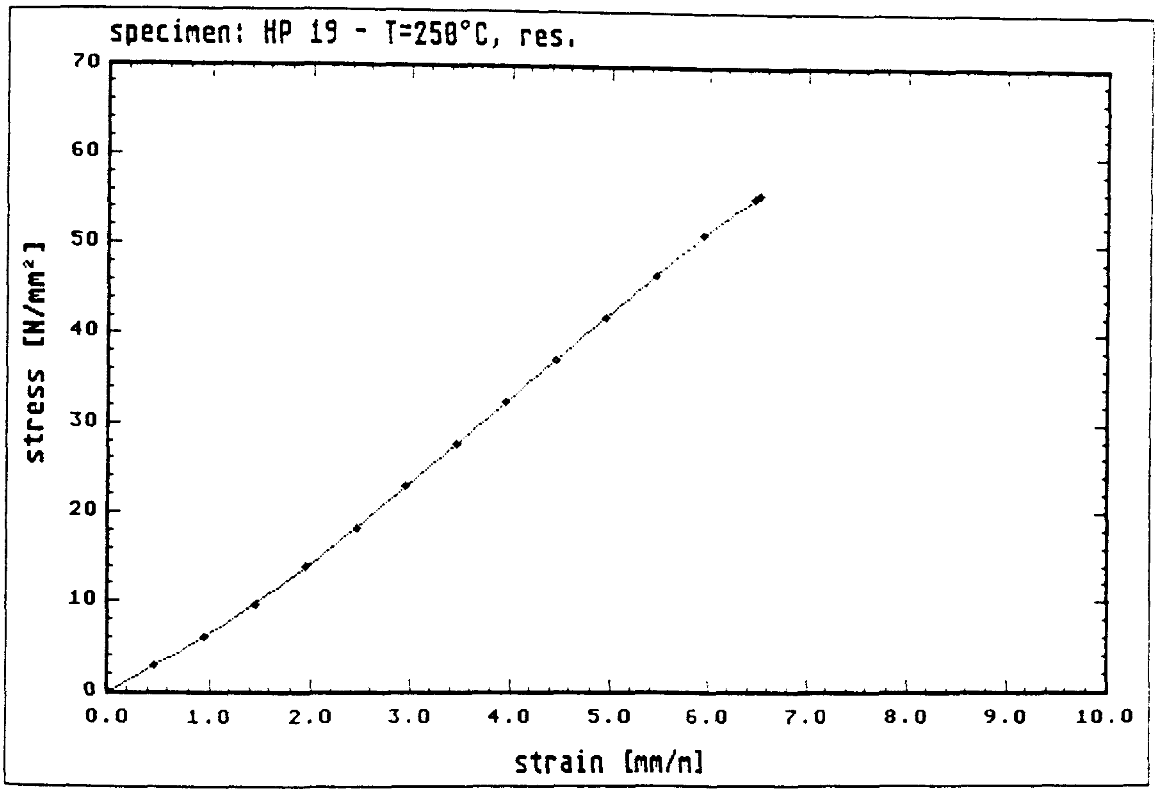

specimen: HP 2-12 - T=450°C
70
60
50
40
30
20
10
0
stress [N/mm²]
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

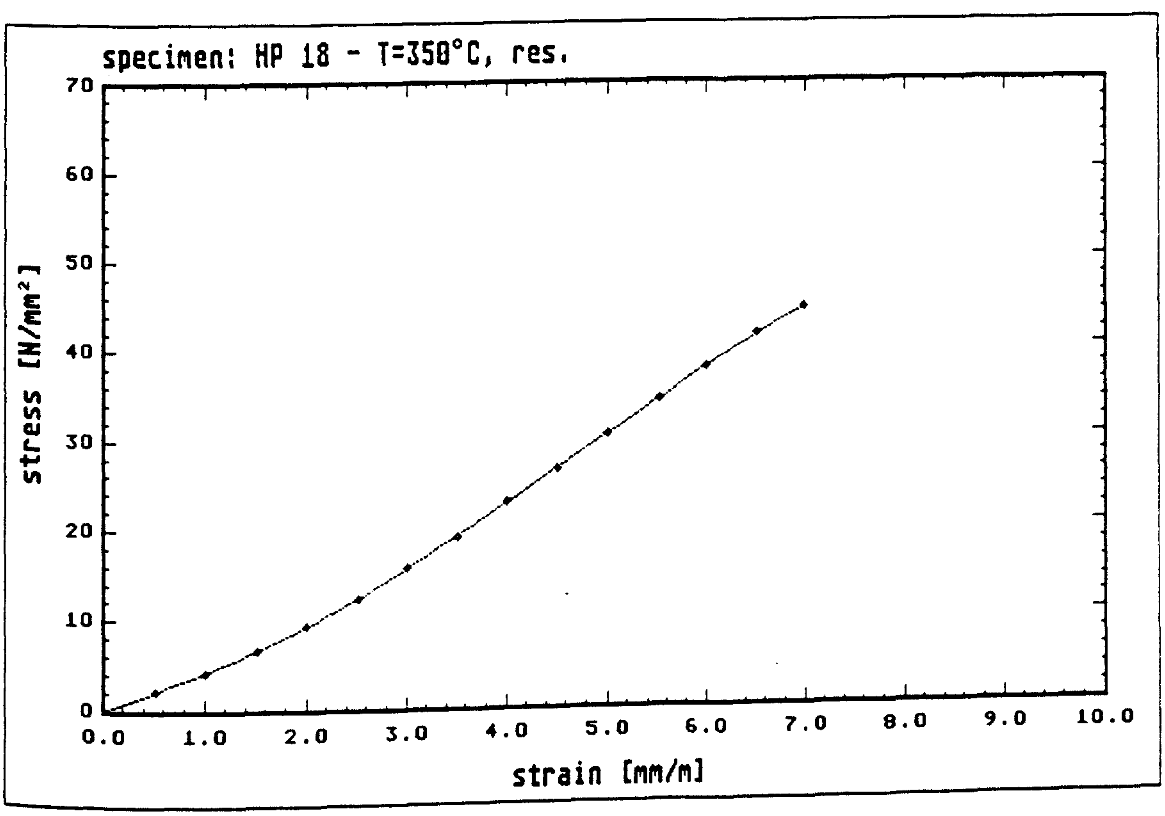

specimen: HP 2-13 - T=450°C
70
60
50
40
30
20
10
0
stress [N/mm²]
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]


specimen: HP 2-14 - T=600°C
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]


specimen: HP 2-15 - T=600°C
stress [N/mm²]
0
10
20
30
40
50
60
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]


specimen: HP 2-16 - T=600°C
stress [N/mm²]
70
60
50
40
30
20
10
0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]


specimen: HP 19 - T=250°C, res.
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]


specimen: HP 18 - T=350°C, res.
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

Dr. Diederichs

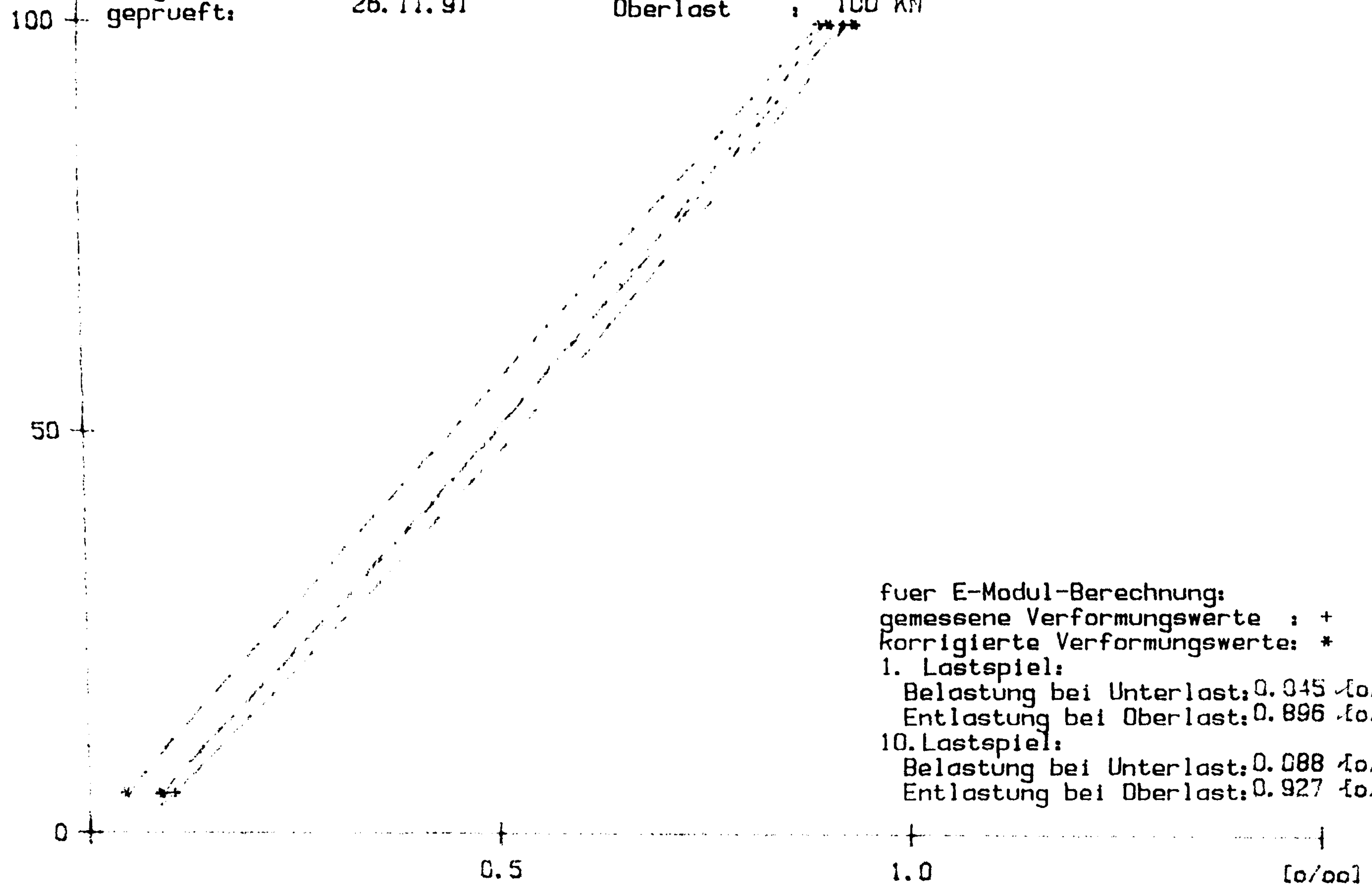
HSC LWA

8762 / 8762

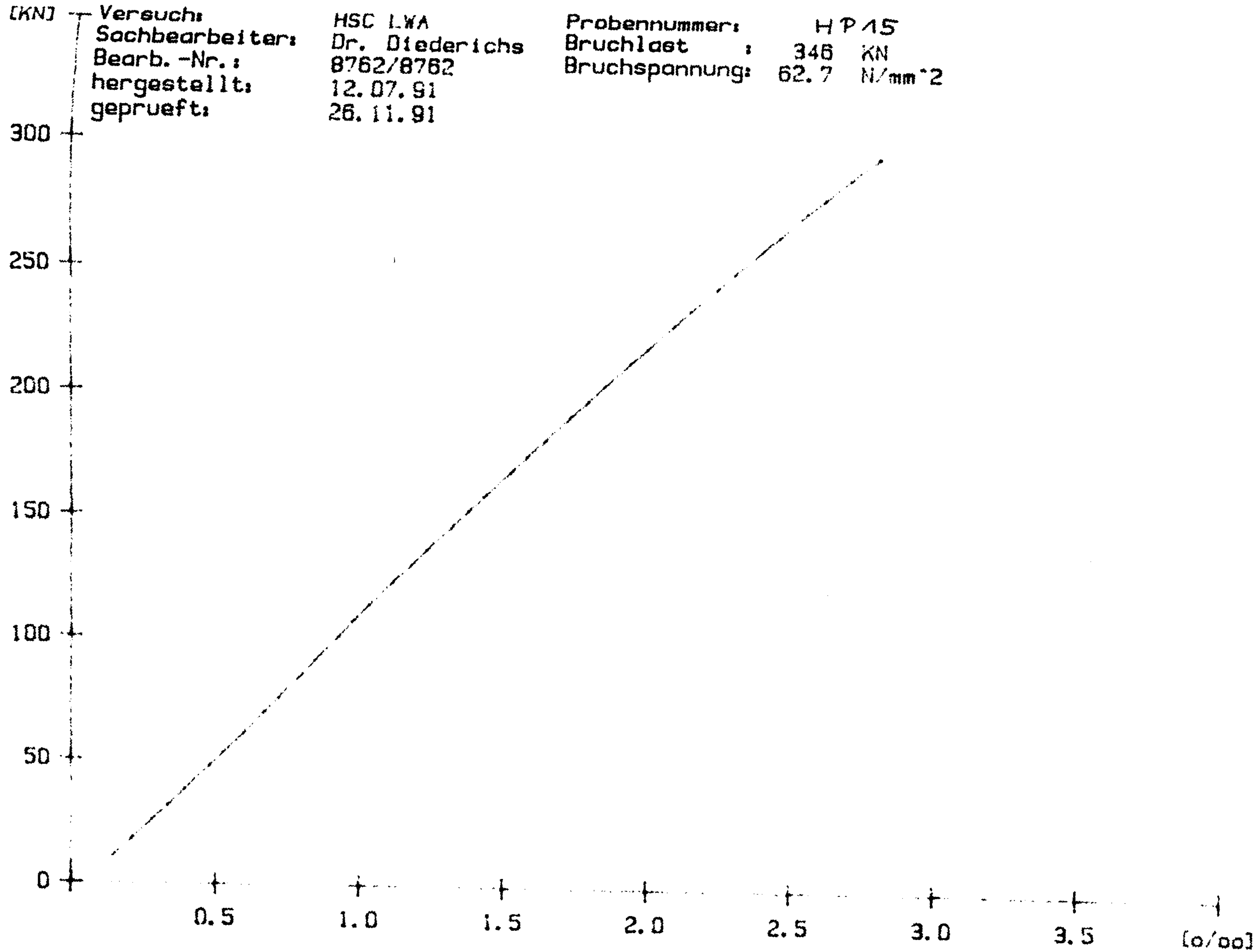
Nr.	Filename	Ø (cm)	Höhe (cm)	Masse lufttrock. (kg)	Rohdichte lufttrock. (kg/m³)	H/Ø	Voraussichtliche Bruchlast β_c (N/mm²)	Unterlast (KN)	Oberlast (KN)	Voraussichtliche Bruchlast (KN)	Bruchlast FU (KN)	Fläche A (mm²)	β_{Dr} (N/mm²)	
1	D-HP2-3	7,93	30,02	2,819	1901	3,79	55	5	100	300	301,9	4938,97	61,13	Knall
2	D-HP-15	8,38	29,60	3,076	1884	3,53	55	5	100	300	346,0	5515,41	62,73	* Knall
Mi	—	—	—	—	1893	—	—	—	—	—	—	—	61,93	—
3	D-HP2-4	7,93	30,02	2,780	1875	3,79	55	5	100	300	300,3	4938,97	60,80	Knall
4	D-HP-16	8,38	29,40	2,973	1833	3,51	55	5	100	300	337,0	5515,41	61,10	Knall
Mi	—	—	—	—	1854	—	—	—	—	—	—	—	60,95	—
5	D-HP2-5	7,93	30,04	2,665	1796	3,79	55	5	100	300	285,9	4938,97	57,91	Knall
6	D-HP-17	8,38	29,55	2,903	1781	3,53	55	5	90	270	339,0	5515,41	61,46	Knall
Mi	—	—	—	—	1789	—	—	—	—	—	—	—	59,68	—

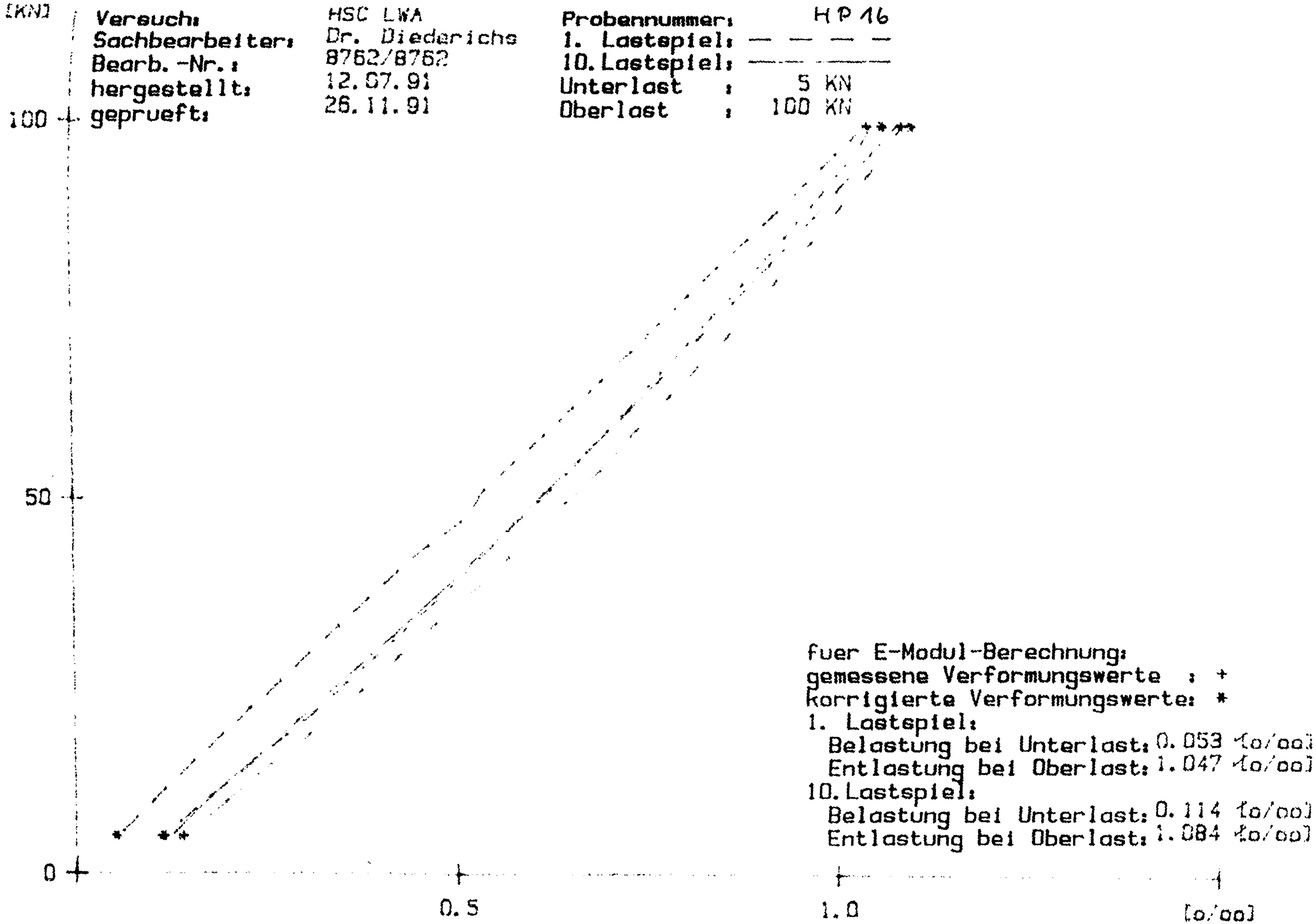
1	HP 2-3	100°C
2	HP 15	100°C
3	HP 2-4	150°C
4	HP 16	150°C
5	HP 2-5	200°C
6	HP 17	200°C

Versuch:	HSC LWA	Probennummer:	HP15
Sachbearbeiter:	Dr. Diederichs	1. Lastspiel:	— — — —
Bearb.-Nr.:	8762/8762	10. Lastspiel:	————
hergestellt:	12.07.91	Unterlast :	5 KN
geprueft:	26.11.91	Oberlast :	100 KN



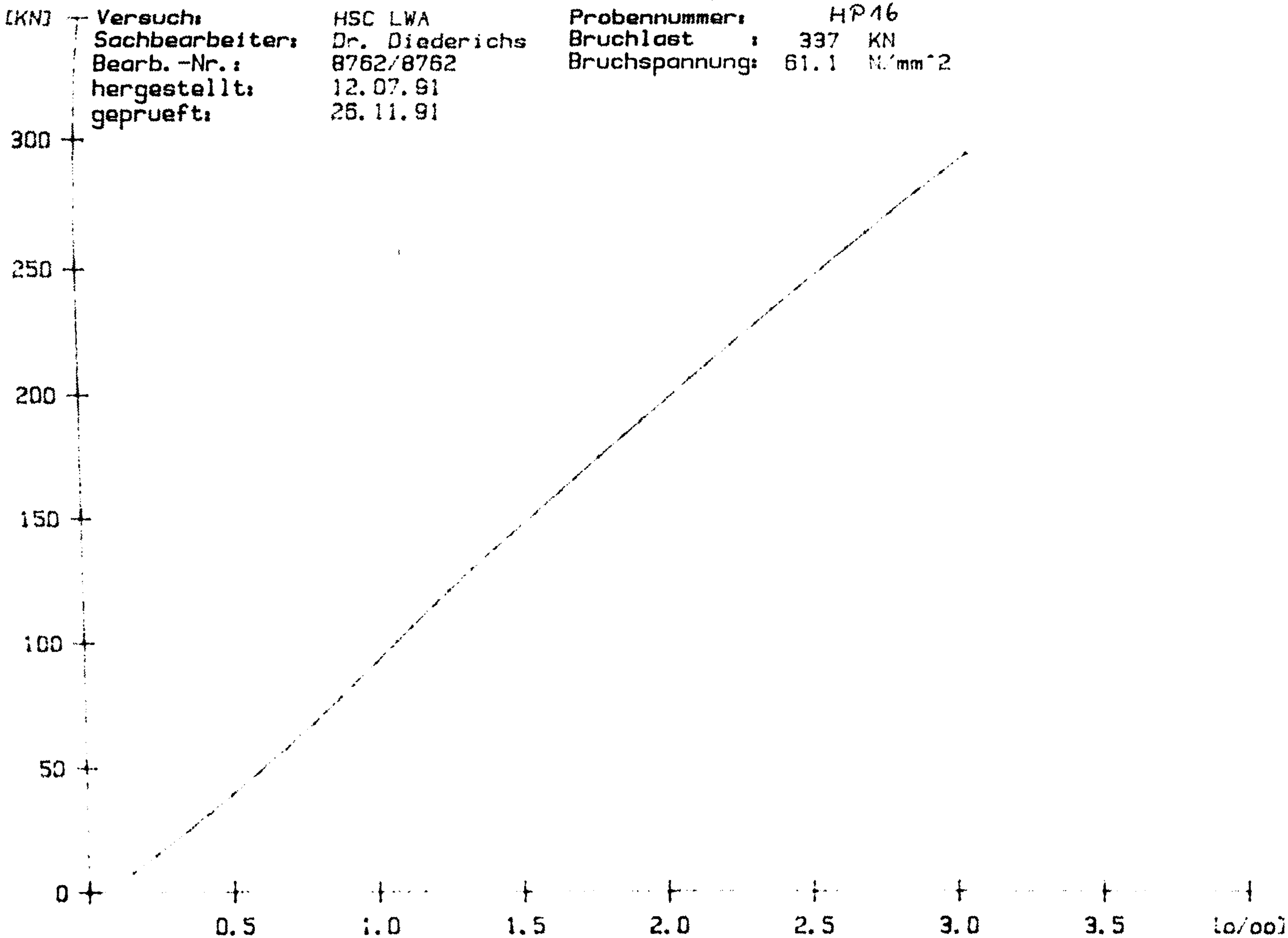
fuer E-Modul-Berechnung:
gemessene Verformungswerte : +
korrigierte Verformungswerte: *
1. Lastspiel:
Belastung bei Unterlast: 0.045 [o/oo]
Entlastung bei Oberlast: 0.896 [o/oo]
10. Lastspiel:
Belastung bei Unterlast: 0.088 [o/oo]
Entlastung bei Oberlast: 0.927 [o/oo]


[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 26.11.91
Probennummer: HP15
Bruchlast : 346 KN
Bruchspannung: 62.7 N/mm^2
300
250
200
150
100
50
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
[o/oo]

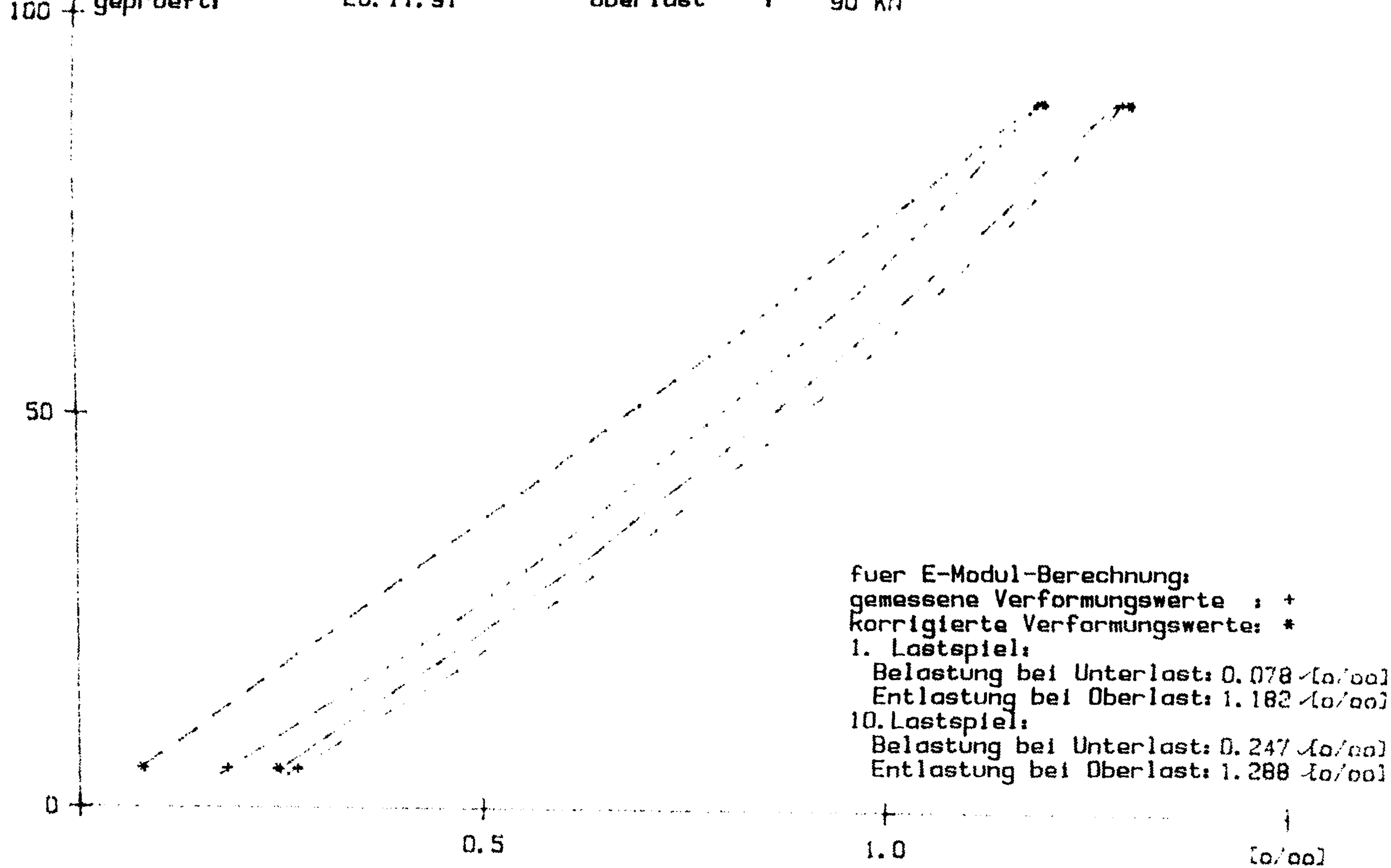

[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 26.11.91
Probennummer: HP 16
1. Lastspiel: — — — —
10. Lastspiel: ————
Unterlast : 5 KN
Oberlast : 100 KN
100
50
0
0.5
1.0
[o/oo]
fuer E-Modul-Berechnung:
gemessene Verformungswerte : +
korrigierte Verformungswerte: *
1. Lastspiel:
Belastung bei Unterlast: 0.053 [o/oo]
Entlastung bei Oberlast: 1.047 [o/oo]
10. Lastspiel:
Belastung bei Unterlast: 0.114 [o/oo]
Entlastung bei Oberlast: 1.084 [o/oo]

Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 26.11.91

Probennummer: HP16
Bruchlast : 337 KN
Bruchspannung: 61.1 N/mm^2

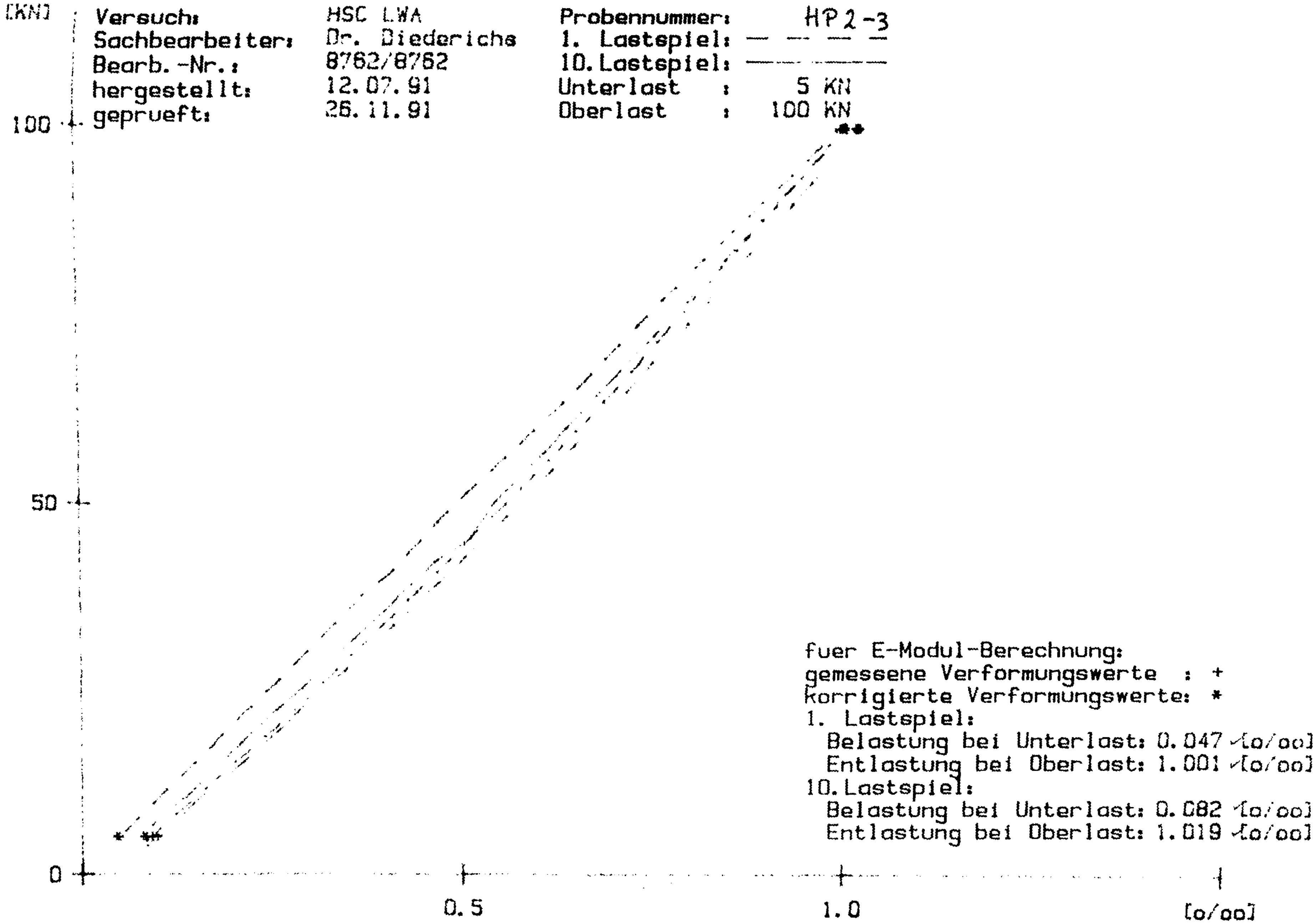


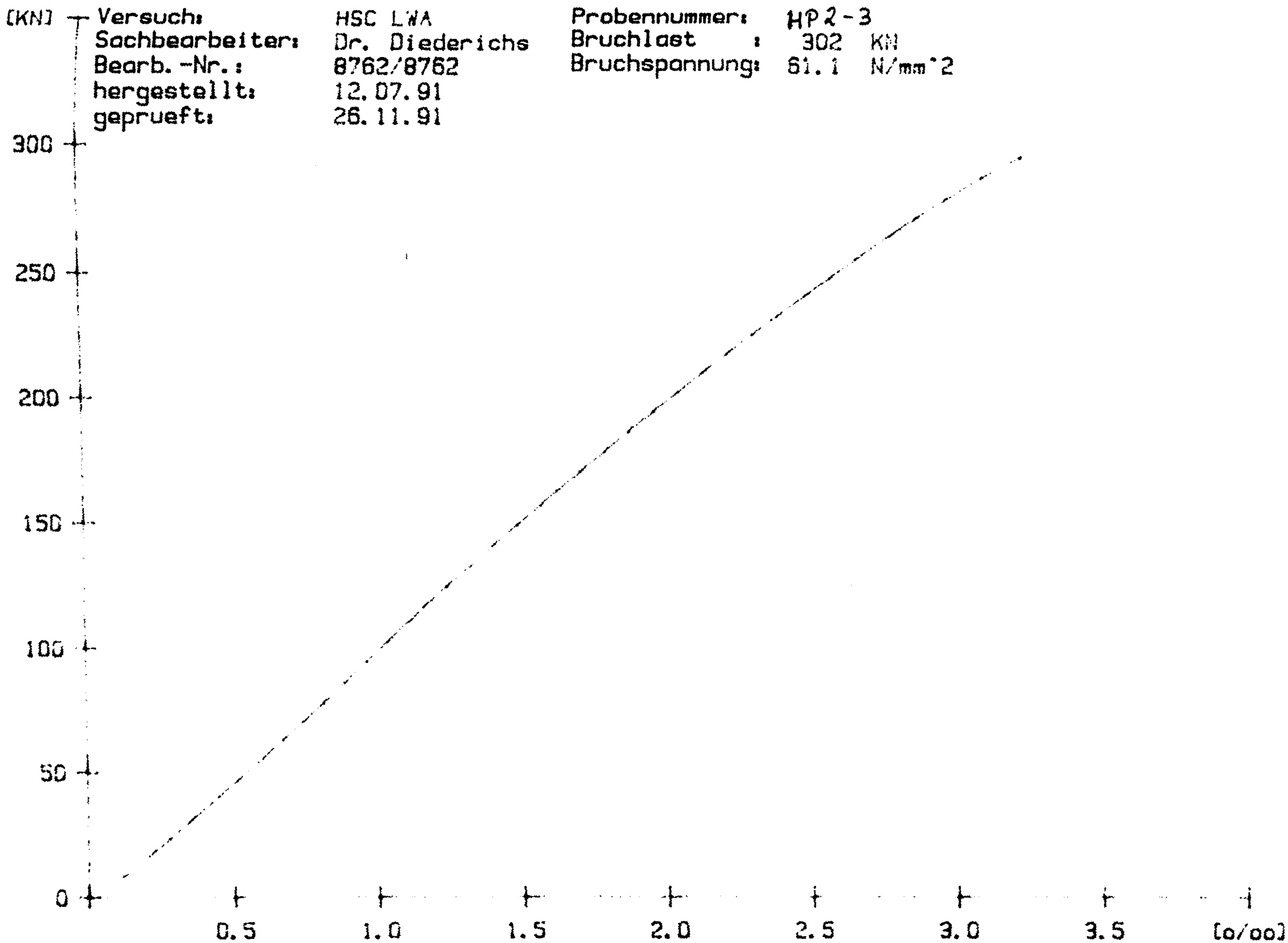
Versuch:	HSC LWA	Probennummer:	HP17
Sachbearbeiter:	Dr. Diederichs	1. Lastspiel:	— — — —
Bearb.-Nr.:	8762/8762	10. Lastspiel:	—— - ———
hergestellt:	12.07.91	Unterlast :	5 KN
geprueft:	26.11.91	Oberlast :	90 KN



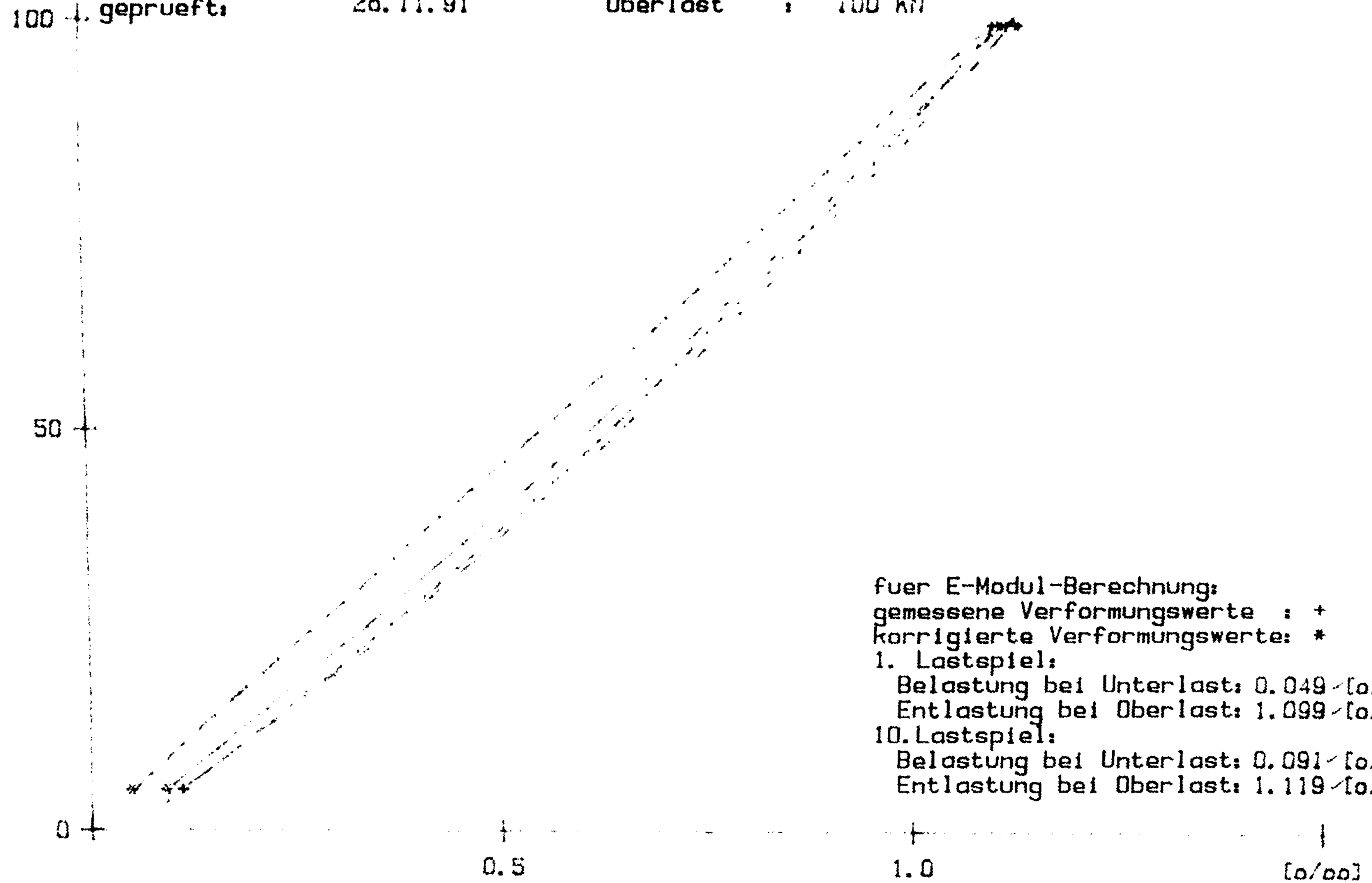
- A 25 -

Versuch:	HSC LWA	Probennummer:	HP 2-3
Sachbearbeiter:	Dr. Diederichs	1. Lastspiel:	— — — —
Bearb.-Nr.:	8762/8762	10. Lastspiel:	————
hergestellt:	12.07.91	Unterlast :	5 KN
geprueft:	26.11.91	Oberlast :	100 KN

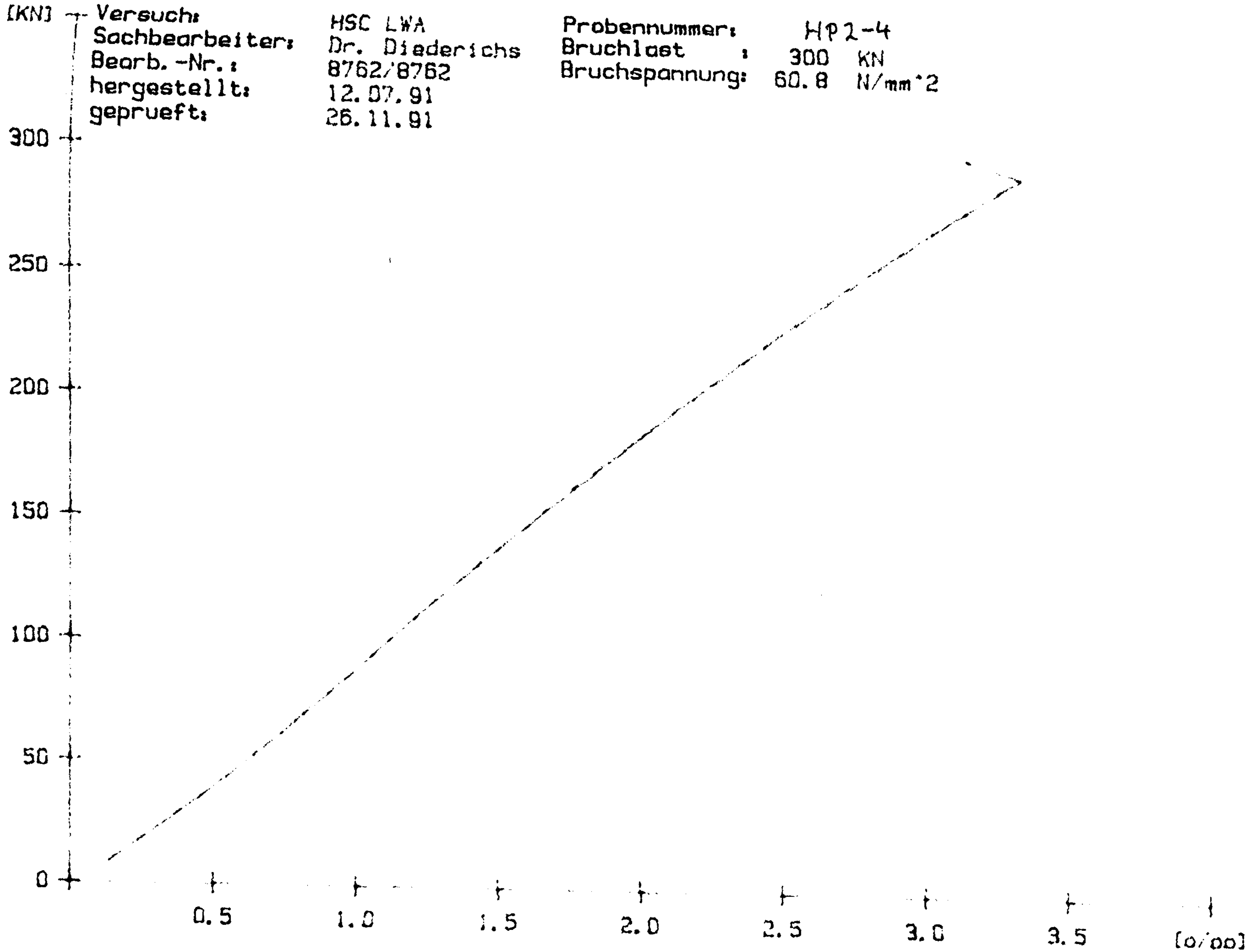


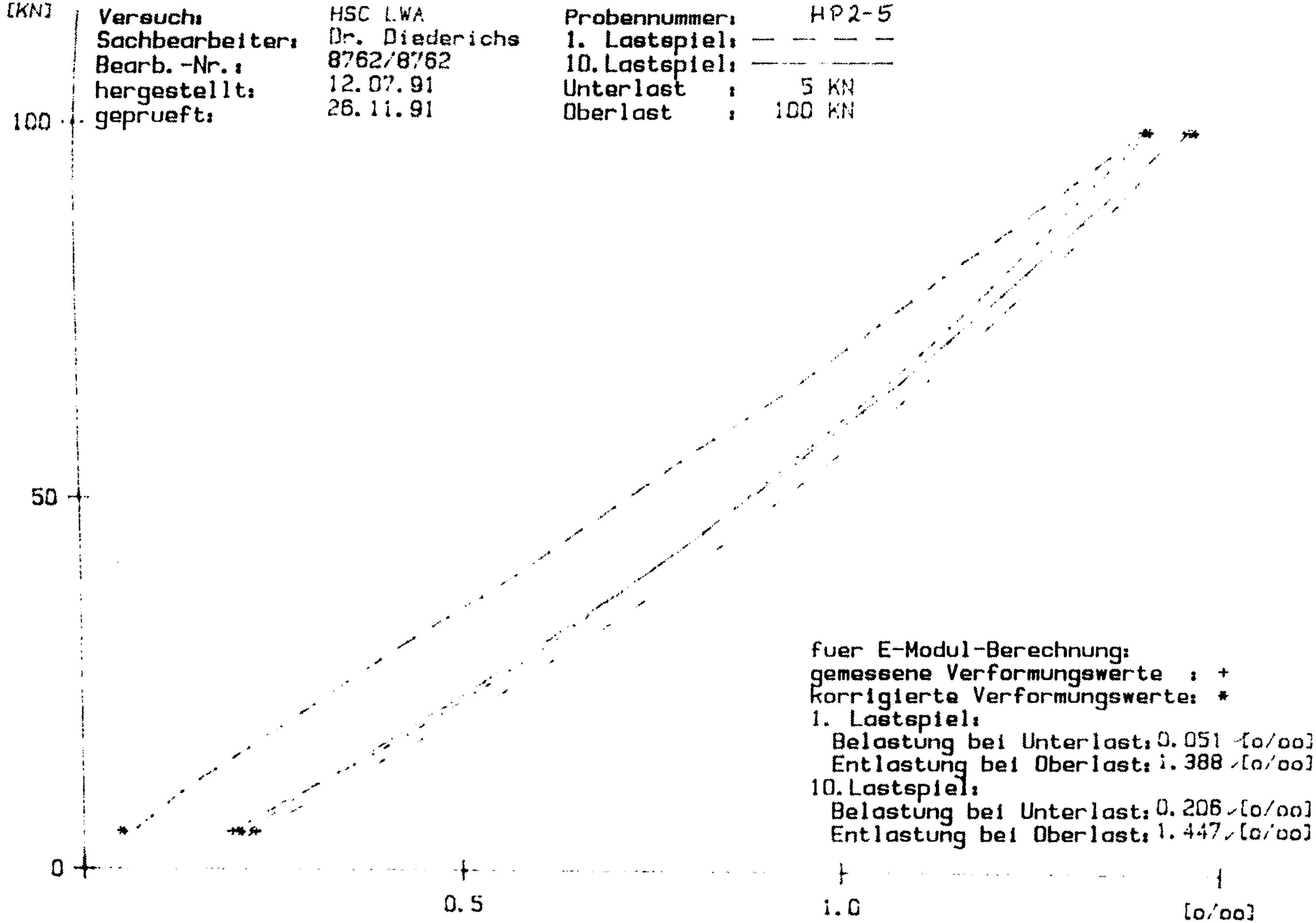

[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 26.11.91
Probennummer: HP2-3
Bruchlast : 302 KN
Bruchspannung: 61.1 N/mm^2
300
250
200
150
100
50
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
[o/oo]

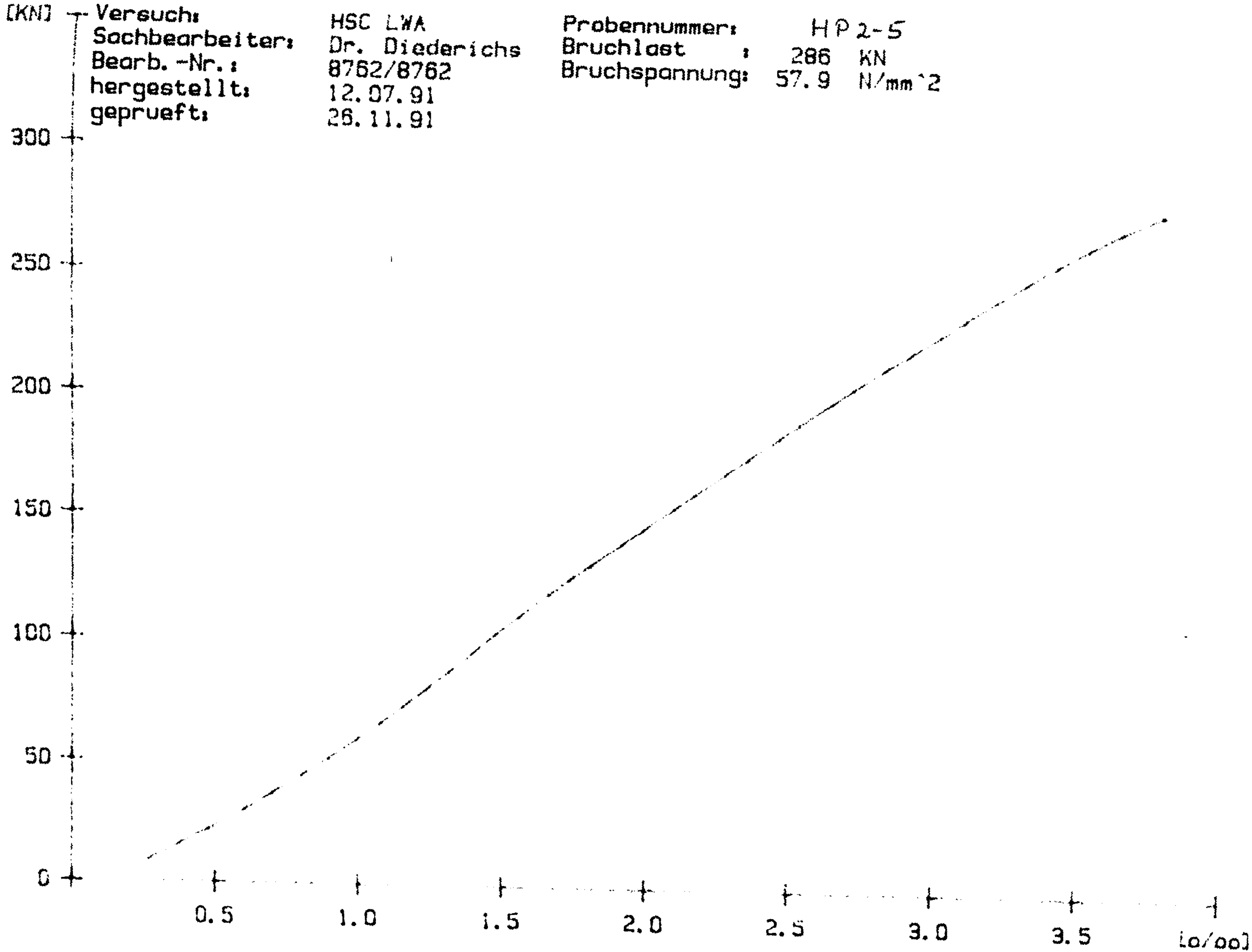
Versuch:	HSC LWA	Probennummer:	HP2-4
Sachbearbeiter:	Dr. Diederichs	1. Lastspiel:	— — — —
Bearb.-Nr.:	8762/8762	10. Lastspiel:	————
hergestellt:	12.07.91	Unterlast :	5 KN
geprueft:	26.11.91	Oberlast :	100 KN

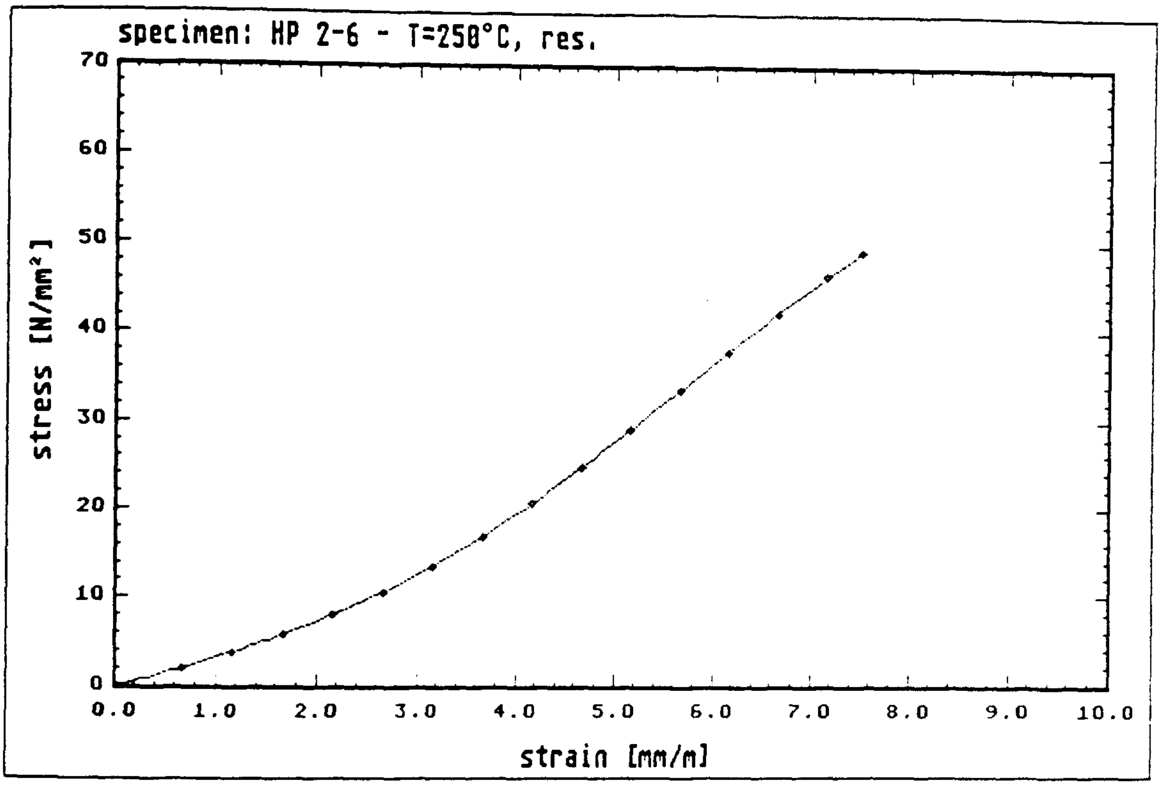


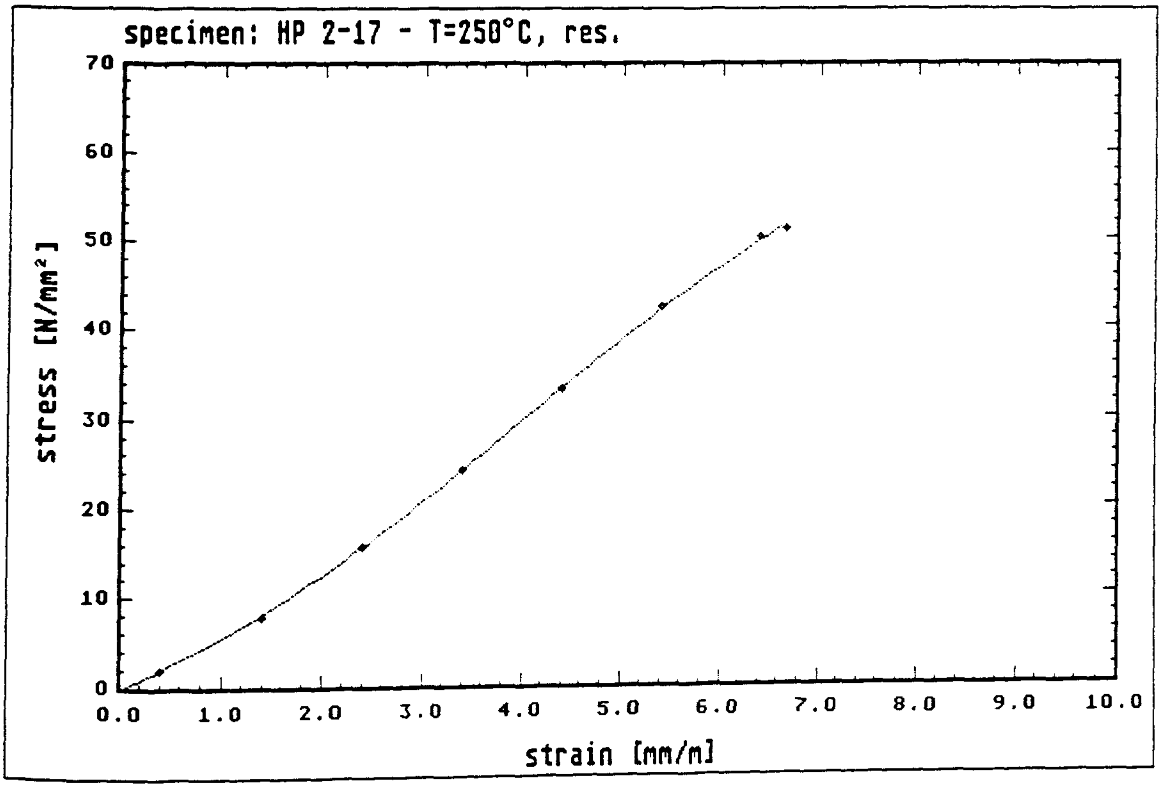
fuer E-Modul-Berechnung:
gemessene Verformungswerte : +
korrigierte Verformungswerte: *
1. Lastspiel:
Belastung bei Unterlast: 0.049 [o/oo]
Entlastung bei Oberlast: 1.099 [o/oo]
10. Lastspiel:
Belastung bei Unterlast: 0.091 [o/oo]
Entlastung bei Oberlast: 1.119 [o/oo]

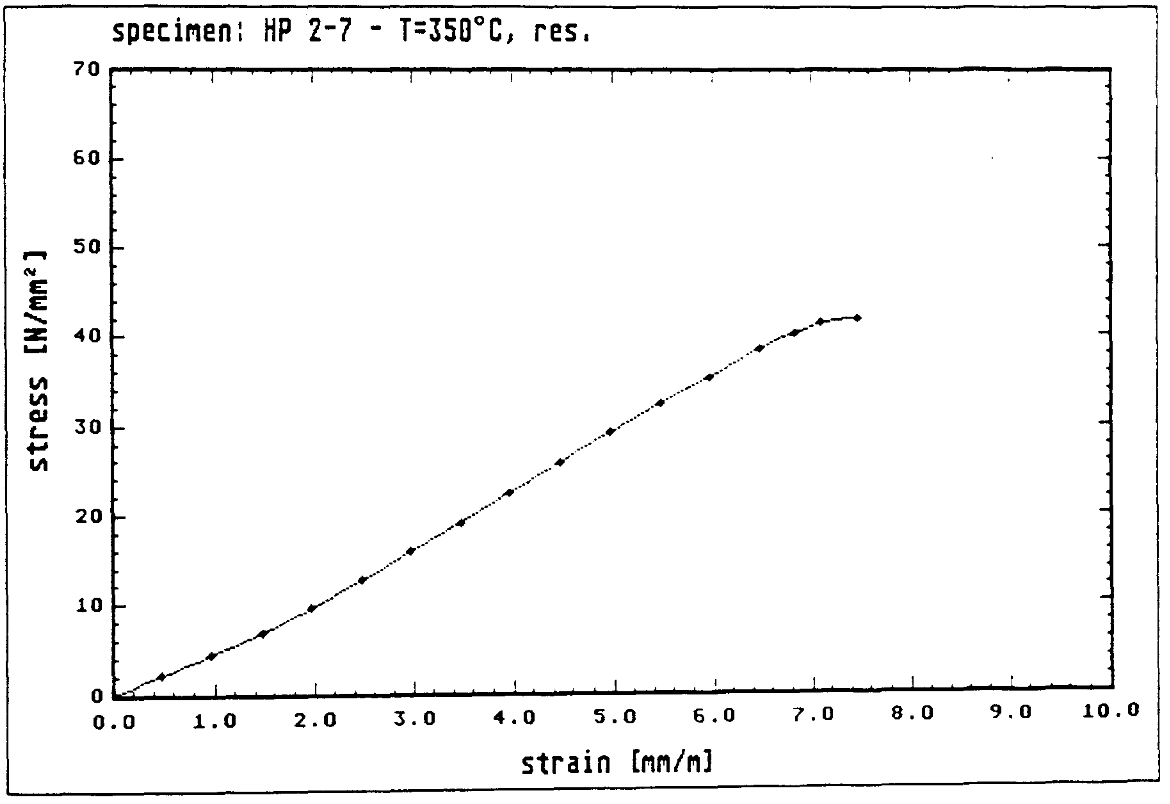

[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 26.11.91
Probennummer: HP2-4
Bruchlast : 300 KN
Bruchspannung: 60.8 N/mm^2
300
250
200
150
100
50
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
[o/oo]


[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 26.11.91
Probennummer: HP2-5
1. Lastspiel:
10. Lastspiel:
Unterlast : 5 KN
Oberlast : 100 KN
100
50
0
0.5
1.0
[o/oo]
fuer E-Modul-Berechnung:
gemessene Verformungswerte : +
korrigierte Verformungswerte: *
1. Lastspiel:
Belastung bei Unterlast: 0.051 [o/oo]
Entlastung bei Oberlast: 1.388 [o/oo]
10. Lastspiel:
Belastung bei Unterlast: 0.206 [o/oo]
Entlastung bei Oberlast: 1.447 [o/oo]


[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 26.11.91
Probennummer: HP 2-5
Bruchlast : 286 KN
Bruchspannung: 57.9 N/mm`2
300
250
200
150
100
50
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
[o/oo]


specimen: HP 2-6 - T=250°C, res.
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]


specimen: HP 2-17 - T=250°C, res.
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]


specimen: HP 2-7 - T=350°C, res.
stress [N/mm²]
0
10
20
30
40
50
60
70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
strain [mm/m]

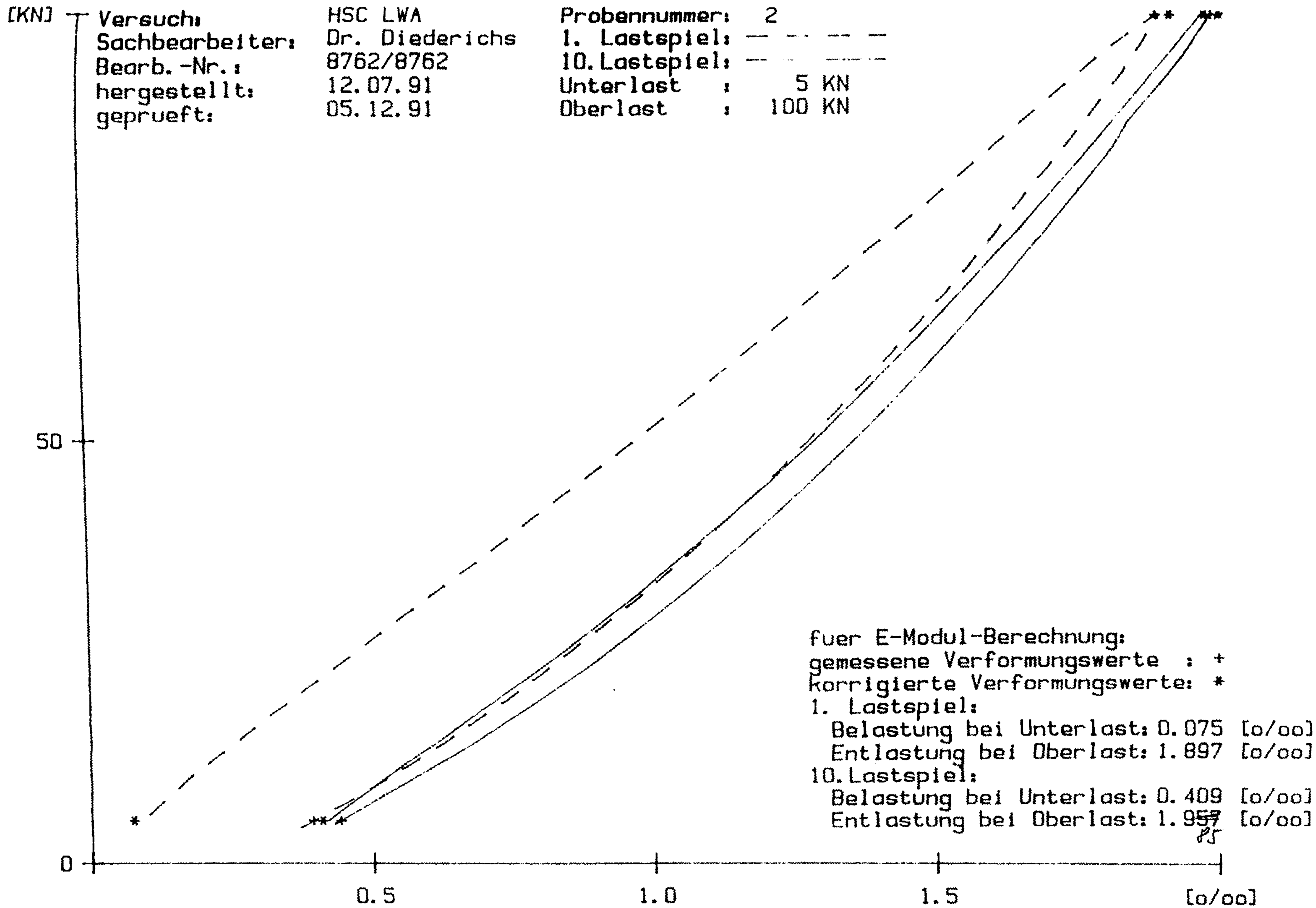
Dr. Diederichs

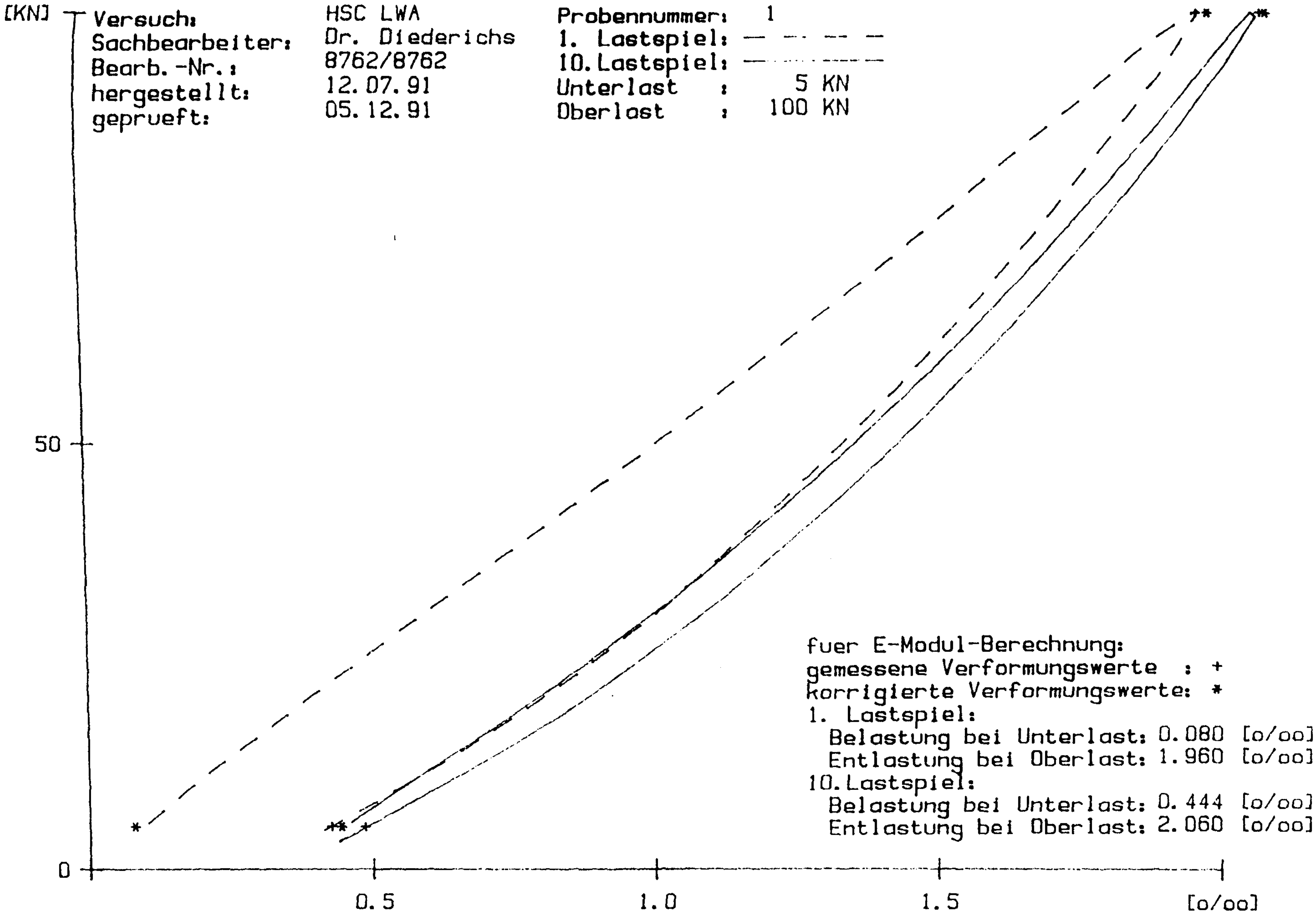
HSC LWA

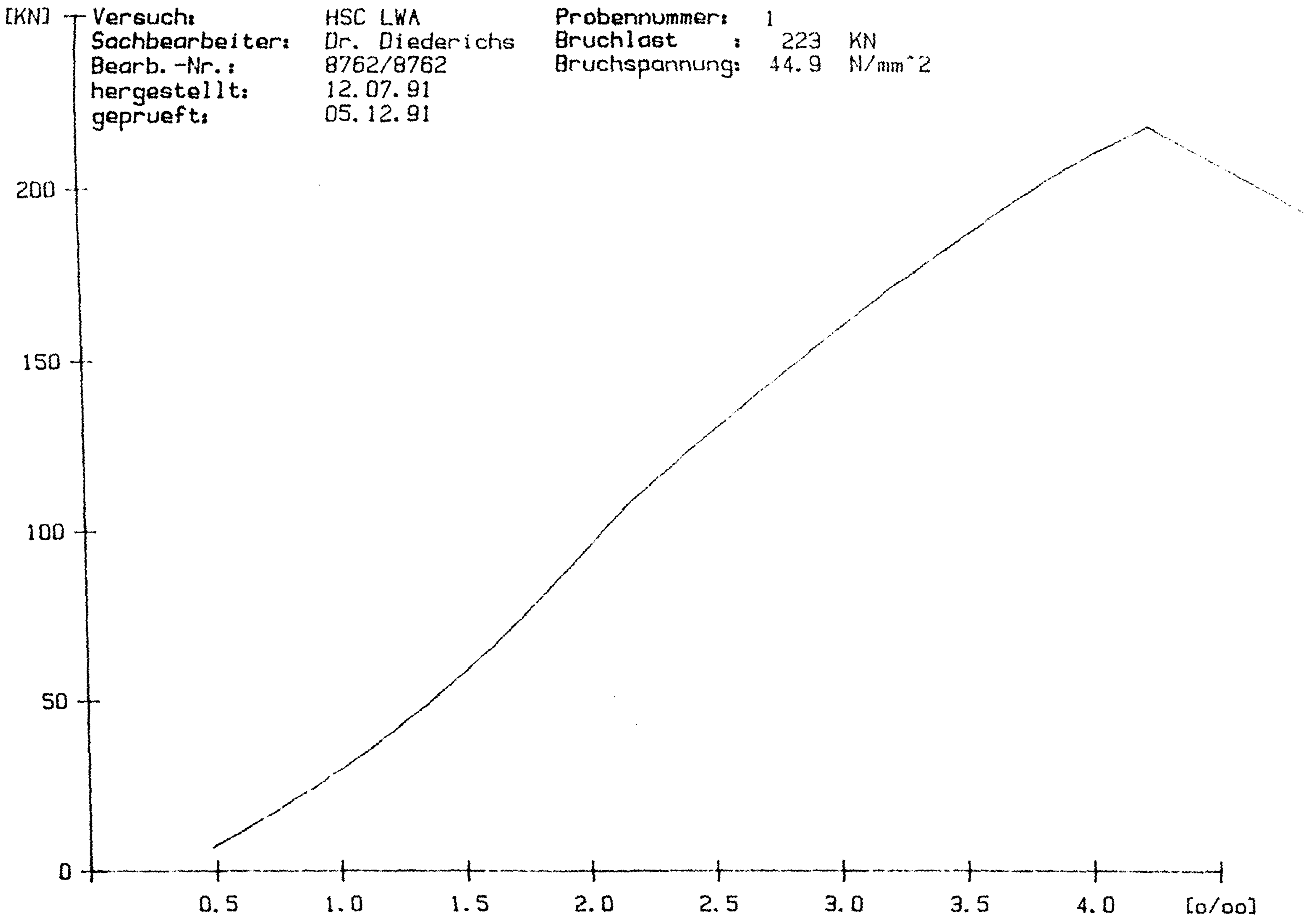
Disc. Nr. DHS-9

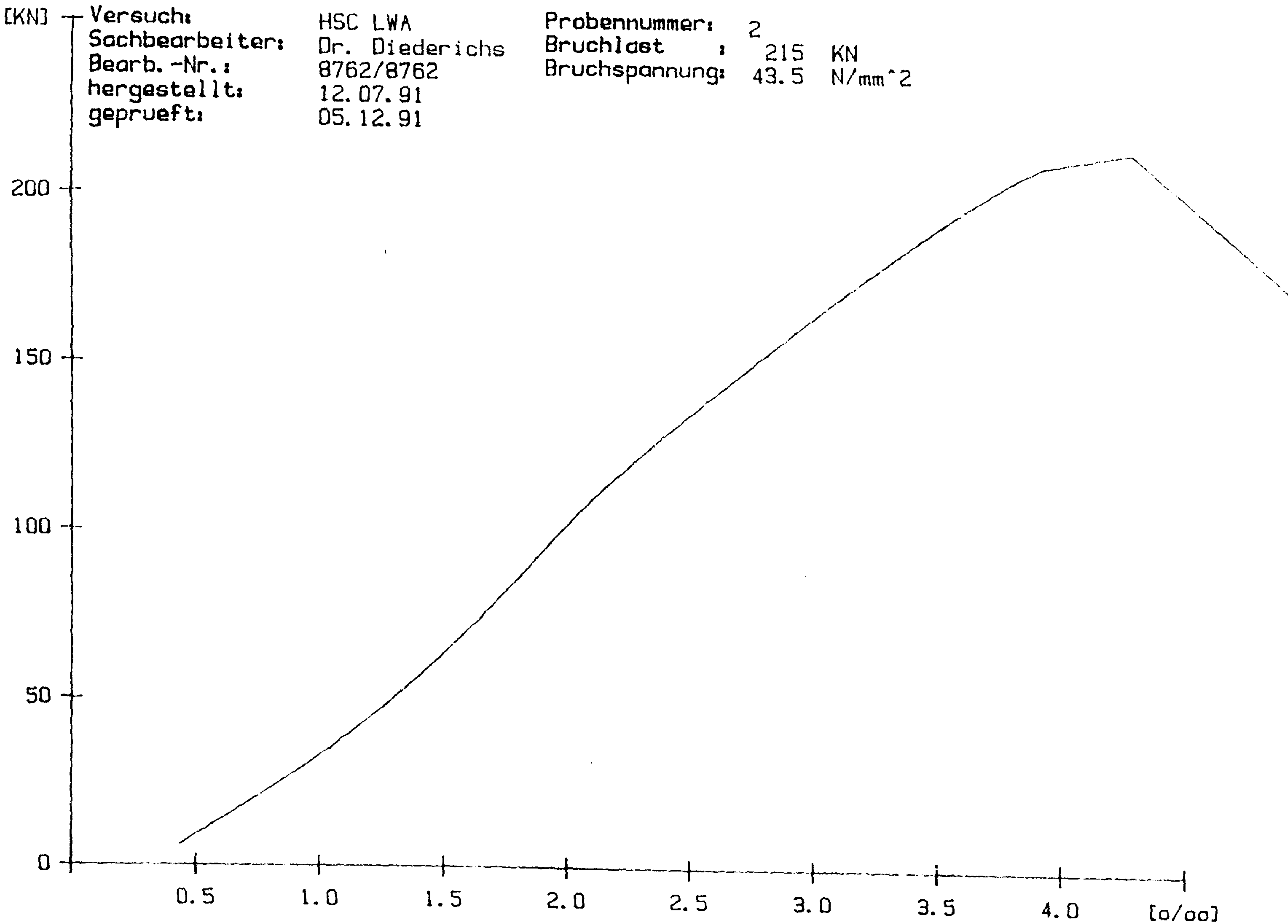
Nr.	Filename	Ø (cm)	Höhe (cm)	Masse lufttrck. (kg)	Rohdichte lufttrck. (kg/m³)	H/Ø	Voraussichtliche Bruchlast β_c (N/mm²)	Unterlast (KN)	Oberlast (KN)	Voraussichtliche Bruchlast (KN)	Bruchlast FU (KN)	Fläche A (mm²)	β_{Dr} (N/mm²)
1	D-HP2-18	7,94	30,05	2,643	1,776	3,78	60	5	100	300	222,5	4951,43	44,9
2	D-HP2-19	7,94	30,04	2,637	1,773	3,78	60	5	100	300	215,4	4951,43	43,5
Mi	—	—	—	—	1,775	—	—	—	—	—	—	—	44,2
1	HP 2-18												
2	HP 2-19												

hergestellt am: 12.07.91 geprüft am: 05.12.91 Alter 146 Tage

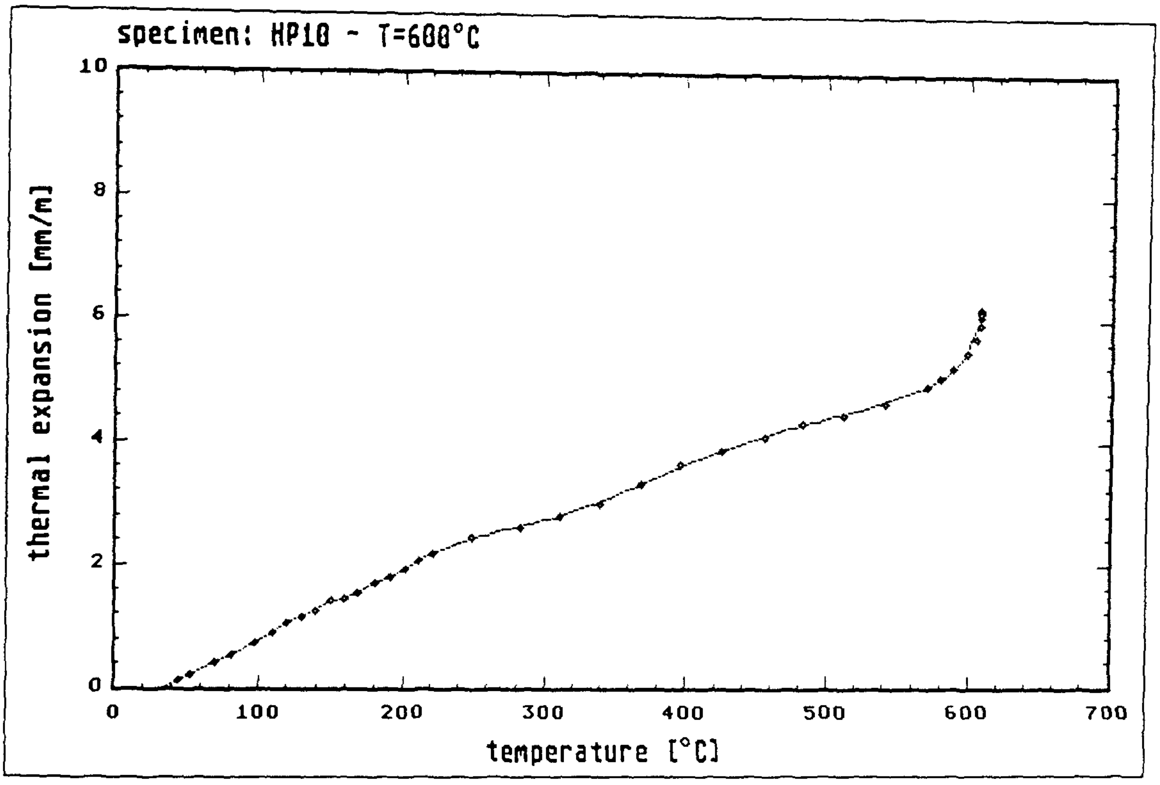

[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 05.12.91
Probennummer: 2
1. Lastspiel:
10. Lastspiel:
Unterlast : 5 KN
Oberlast : 100 KN
50
0
0.5
1.0
1.5
[o/oo]
fuer E-Modul-Berechnung:
gemessene Verformungswerte : +
korrigierte Verformungswerte: *
1. Lastspiel:
Belastung bei Unterlast: 0.075 [o/oo]
Entlastung bei Oberlast: 1.897 [o/oo]
10. Lastspiel:
Belastung bei Unterlast: 0.409 [o/oo]
Entlastung bei Oberlast: 1.9~~57~~ [o/oo]
85

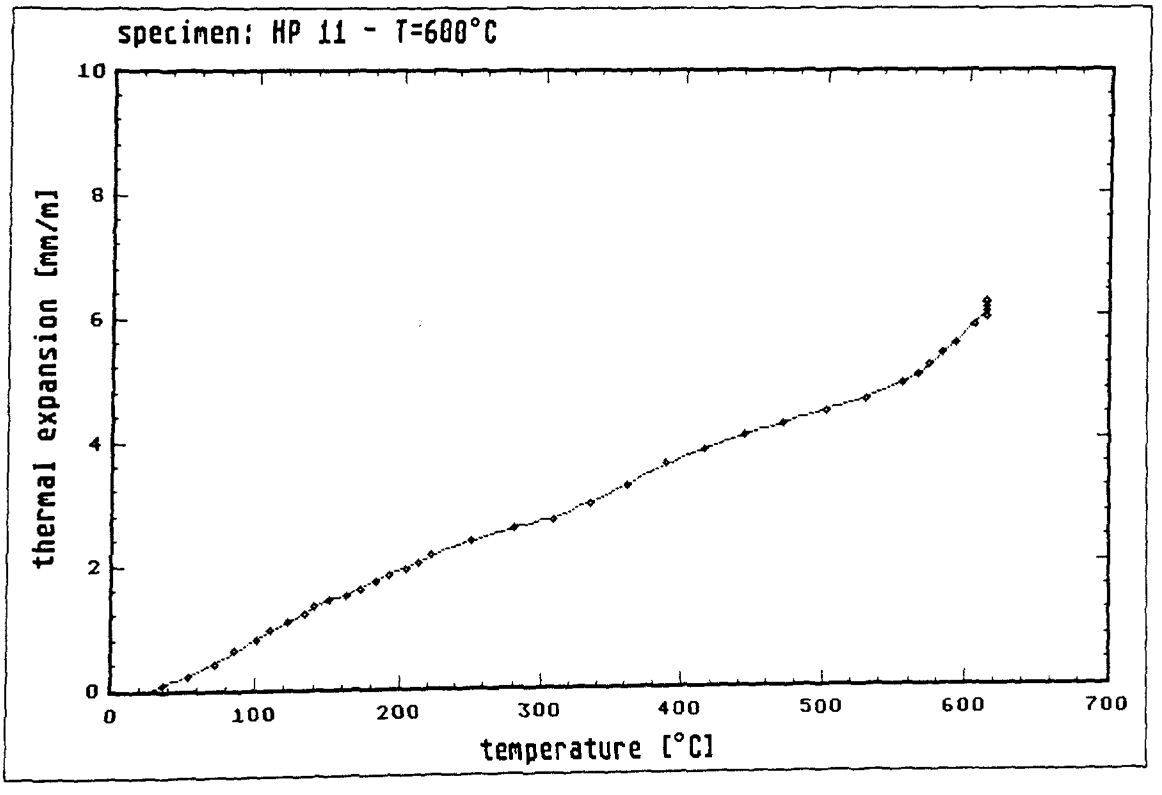

[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 05.12.91
Probennummer: 1
1. Lastspiel:
10. Lastspiel:
Unterlast : 5 KN
Oberlast : 100 KN
50
0
0.5
1.0
1.5
[o/oo]
fuer E-Modul-Berechnung:
gemessene Verformungswerte : +
korrigierte Verformungswerte: *
1. Lastspiel:
Belastung bei Unterlast: 0.080 [o/oo]
Entlastung bei Oberlast: 1.960 [o/oo]
10. Lastspiel:
Belastung bei Unterlast: 0.444 [o/oo]
Entlastung bei Oberlast: 2.060 [o/oo]

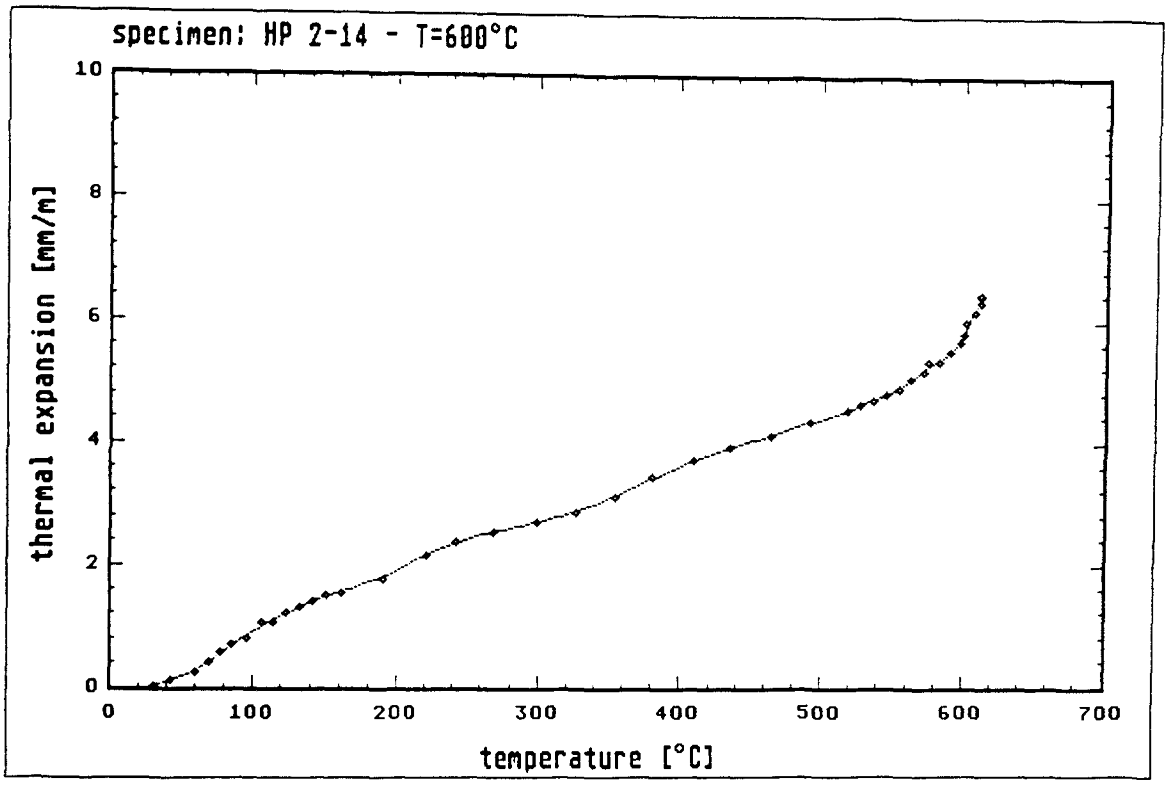

[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 05.12.91
Probennummer: 1
Bruchlast : 223 KN
Bruchspannung: 44.9 N/mm^2
200
150
100
50
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
[o/oo]

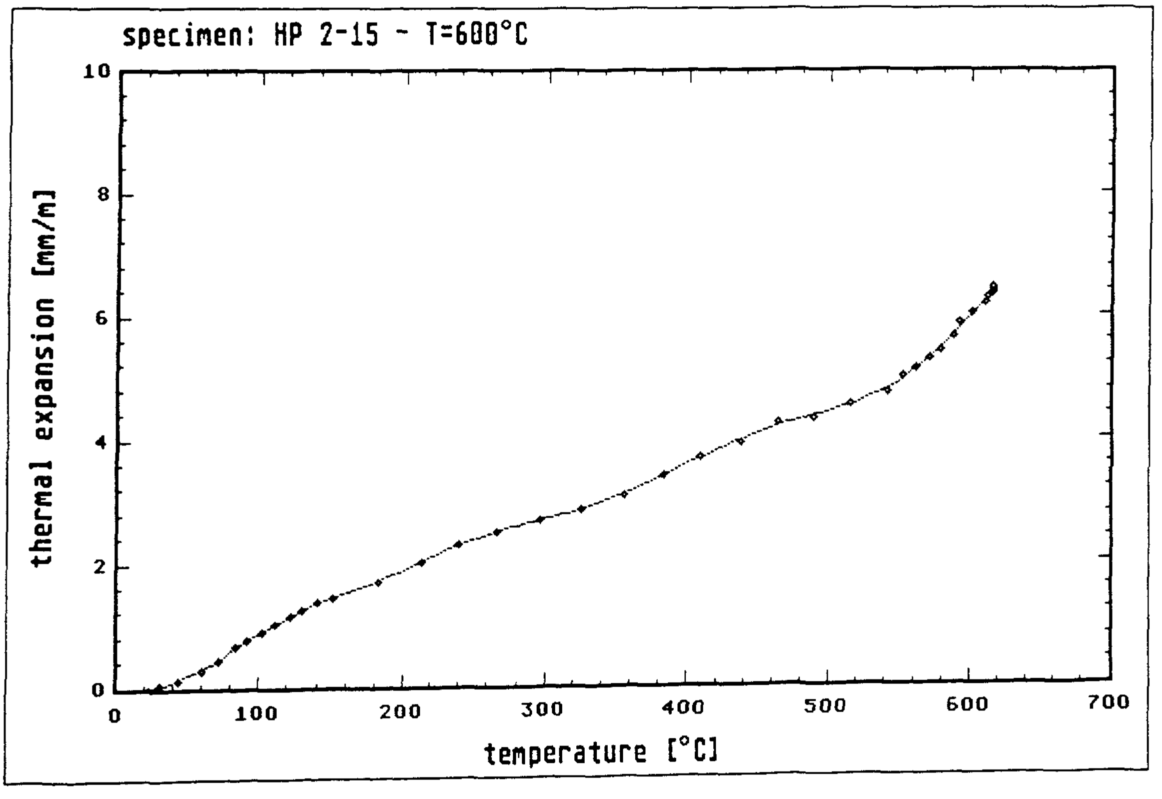

[KN]
Versuch: HSC LWA
Sachbearbeiter: Dr. Diederichs
Bearb.-Nr.: 8762/8762
hergestellt: 12.07.91
geprueft: 05.12.91
Probennummer: 2
Bruchlast : 215 KN
Bruchspannung: 43.5 N/mm^2
200
150
100
50
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
[o/oo]

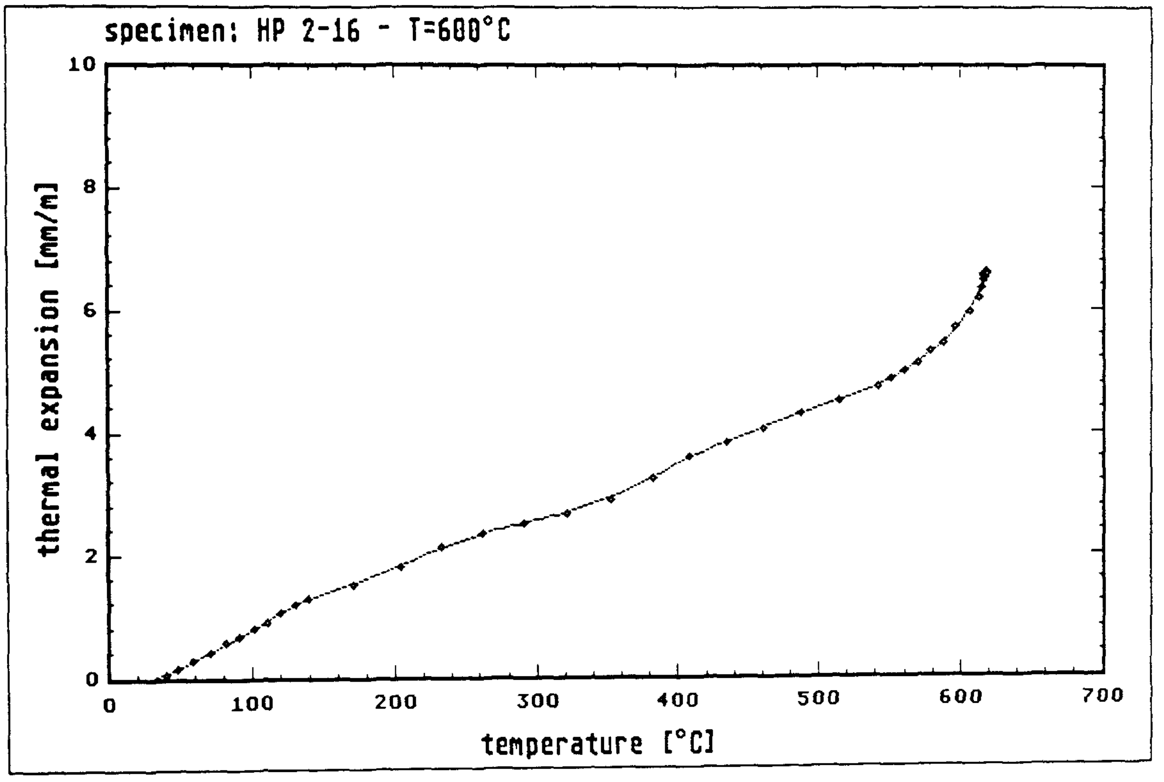
Thermische Dehnung






specimen: HP 2-14 - T=600°C
thermal expansion [mm/m]
temperature [°C]
0
2
4
6
8
10
0
100
200
300
400
500
600
700


specimen: HP 2-15 - T=600°C
thermal expansion [mm/m]
temperature [°C]
0
2
4
6
8
10
0
100
200
300
400
500
600
700


specimen: HP 2-16 - T=600°C
thermal expansion [mm/m]
temperature [°C]
0
2
4
6
8
10
0
100
200
300
400
500
600
700